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Slow Slip History for the MEXICO Subduction Zone: 2005 Through 2011

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Abstract—To further our understanding of the seismically hazardous Mexico subduction zone, we estimate the first time-dependent slip distributions and Coulomb failure stress changes for the six major slow slip events (SSEs) that occurred below Mexico between late 2005 and mid-2011. Slip distributions are the first to be estimated from all continuous GPS data in central and southern Mexico, which better resolves slow slip in space and time than was previously possible in this region. Below Oaxaca, slip during previously un-modeled SSEs in 2008/9 and 2010/11 extended farther to the west than previous SSEs. This constitutes the first evidence that slow slip accounts for deep slip within a previously noted gap between the Oaxaca and Guerrero SSE source regions. The slip that we estimate for the two SSEs that originated below Guerrero between 2005 and 2011 agrees with slip estimated in previous, mostly static-offset SSE modeling studies; however, we show that both SSEs migrated eastward toward the Oaxaca SSE source region. In accord with previous work, we find that slow slip below Guerrero intrudes up-dip into the potentially seismogenic region, presumably accounting for some of the missing slip within the well-described Guerrero seismic gap. In contrast, slow slip below Oaxaca between 2005 and 2011 occurred mostly down-dip from the seismogenic regions defined by the rupture zones of large thrust earthquakes in 1968 and 1978 and released all of the slip deficit that accumulated in the down-dip region during this period.

Key words: Slow slip events, earthquake cycle, Mexico subduction zone, global positioning system.

1. Introduction

With the increase in continuous GPS (cGPS) stations deployed at subduction zones worldwide, our understanding of how plate motion is accommodated at these convergent margins is evolving rapidly. Slow slip observed in cGPS position time series, in conjunction with seismically detected tectonic tremor, have helped to define a complex transition zone between stick–slip and creep behavior along the subduction zone interface (Dragert *et al.* 2001; Lowry *et al.* 2001; Ohta *et al.* 2004, 2006). The location of many slow slip events (SSEs) immediately down-dip from seismogenic zones suggests they could trigger large thrust earthquakes. For example, the 11 March 2011 $M_w = 9.0$ Tohoku-Oki earthquake in Japan (Ito *et al.* 2012), 20 March 2012 $M_w = 7.4$ Ometepec earthquake on the Mexico subduction zone (Graham *et al.* 2014a), and 2014 $M_w = 8.1$ Iquique earthquake in Chile (Ruiz *et al.* 2014) were all preceded by SSEs close to or overlapping the eventual earthquake rupture zones. Numerical simulations of slow slip suggest that repeated SSEs in the transition zone between stick–slip and creep concentrate stress at the down-dip limit of the seismogenic zone, which in turn increases the probability that a future SSE will evolve into a dynamic rupture (Segall and Bradley 2012). SSEs also relieve interseismic strain accumulated along the plate interface, thereby limiting the size of coseismic rupture patches and consequently reducing subsequent earthquake magnitudes (Dixon *et al.* 2014). Measurements and modeling of SSEs are thus important for seismic hazard analysis and for an improved understanding of how subduction zones accommodate convergence.

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SSE characteristics vary globally, exhibiting a wide range of durations, locations on the plate interface, recurrence intervals, magnitudes, and slip amplitudes (e.g., Peng and Gomberg 2010; Beroza and Ide 2011). Slow slip has also been shown to migrate along the plate interface, in some places up to 300 km along-strike (e.g., Schmidt and Gao 2010; Dragert and Wang 2011). In addition to slip migration along a fault, simulations of SSEs using rate-and-state-dependent friction indicate that slow slip can also nucleate simultaneously on distant regions of a fault (Colella *et al.* 2011, 2012). Moreover, Wallace *et al.* (2012) postulate that SSEs can interact with one another and infer from Coulomb failure stress calculations that a deep slow slip event along the Hikurangi subduction zone in New Zealand may have triggered a series of subsequent, shallower SSEs.

Between 1993, when the first continuous GPS receiver was installed along the Mexico subduction zone (MSZ), and late 2012, at least 15 SSEs were recorded along the subduction interface below the Mexican states of Guerrero and Oaxaca (Fig. 1) (e.g., Kostoglodov *et al.* 2003; Brudzinski *et al.* 2007; Correa-Mora *et al.* 2008, 2009; Radiguet *et al.* 2012). In addition, smaller SSEs, may have occurred, presently below the threshold of GPS detection (Vergnolle *et al*. 2010). Before ∼2005, continuous GPS stations were clustered primarily in Guerrero and in central Oaxaca, with only a handful of stations located in the ∼200-km gap between the station clusters. Continuous receivers operating in Guerrero have detected SSEs every 3–4 years within a region that extends ∼250 km along-strike and up-dip into the seismogenic zone of the Guerrero seismic gap (Fig. 1) (Radiguet *et al.* 2012). The magnitude of slow slip on the interface has reached a maximum of ∼200 mm, accounting for the slip equivalent of an $M \sim 7.5$ earthquake (e.g., Lowry *et al.* 2001; Kostoglodov *et al.* 2003; Iglesias *et al.* 2004; Yoshioka *et al.* 2004; Larson *et al.* 2007; Radiguet *et al.* 2012; Cavalié *et al.* 2013). Along the Oaxaca segment, slow slip has occurred every 1–2 years with smaller maximum slip amplitudes of ∼100 mm and smaller

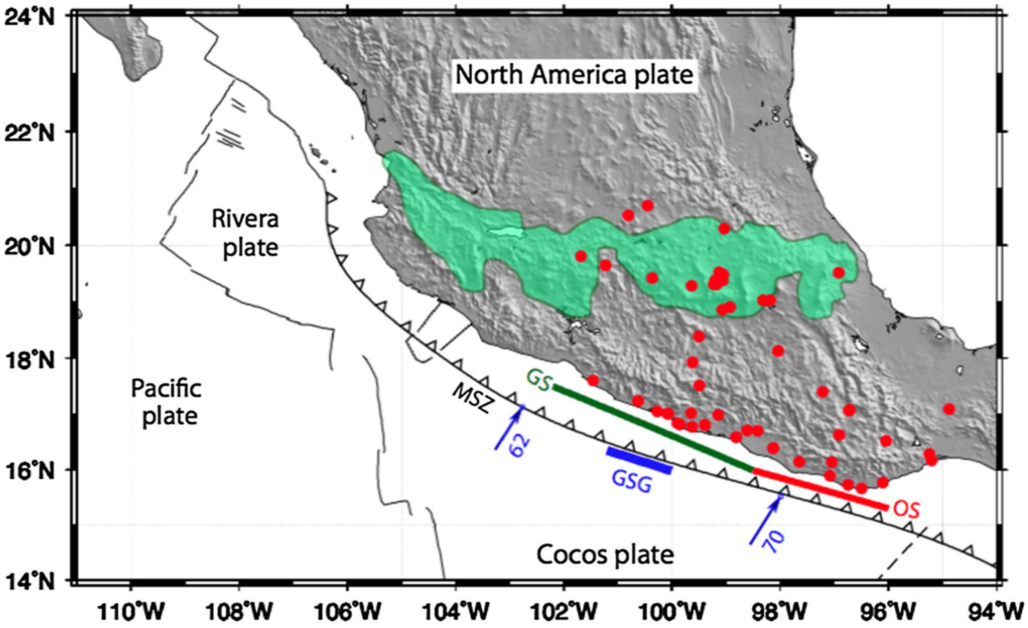


Figure 1

Tectonics of the study area. Convergence velocities for the Cocos plate relative to the North America plate are shown by blue vectors. Convergence rates are given in mm/year (DeMets *et al.* 2010). The *green* and *red lines* demarcate the along-strike limits of the Guerrero segment (GS) and Oaxaca segment (OS), respectively. The *thick blue line* illustrates the northwestern Guerrero seismic gap (GSG) after Radiguet *et al.* (2012). *Red circles* denote locations of GPS sites used to model the SSEs. *Green area* shows the Mexican Volcanic Belt. *MSZ* Mexico Subduction Zone moment releases of M 6.6–6.9 than for Guerrero (Correa-Mora *et al.* 2008, 2009; Graham *et al.* 2014a).

The principal goal of this study is to undertake the first time-dependent modeling of a complete sequence of slow slip events along the Mexico subduction zone, including previously un-modeled SSEs in 2008/9 and 2010/11 beneath Oaxaca and four additional SSEs below Guerrero and Oaxaca. Radiguet *et al.* (2011) completed the only other SSE time-dependent modeling in Mexico for the 2006 Guerrero SSE. Our focus is on SSEs that have occurred since 2005, when the GPS network geometry in southern Mexico became sufficiently dense to resolve the location and migration of SSEs along the subduction interface. In particular, we seek to determine whether slow slip migrates across the several-hundred-km-wide gap between the Guerrero and Oaxaca regions, as proposed by Franco *et al.* (2005), or whether slow slip in the two regions is spatially and temporally independent, as suggested by Correa-Mora *et al.* (2009). The distinction between localized slow slip regions and wide spread slow slip has important seismic hazard implications for the Mexico subduction zone given that slow slip can load the seismogenic zone or evolve into dynamic rupture. Our analysis includes calculations of Coulomb failure stress changes in response to each SSE to evaluate possible cause-and-effect relationships between the six SSEs that are modeled herein and the 2012 Ometepec earthquake. Our SSE modeling results are the first to be determined from all available continuous GPS stations in southern and central Mexico, which is important for maximizing the spatiotemporal coverage of SSEs in this region.

2. *Data and Methods*

2.1. *GPS Data and Analysis*

2.1.1 *Data, Processing, and Post-Processing Methods*

For this analysis, we use data from 56 continuous GPS stations in central and southern Mexico (Fig. 2) spanning the period January 2005 through October 2011. GPS data were processed with Release 6.1 of the GIPSY software suite from the Jet Propulsion Laboratory (JPL). No-fiducial daily GPS station coordinates were estimated using a precise point-positioning strategy (Zumberge *et al.* 1997), including constraints on a priori tropospheric hydrostatic and wet delays from Vienna Mapping Function (VMF1) parameters (http://ggosatm.hg.tuwien.ac.at), elevation- and azimuthally dependent GPS and satellite antenna phase center corrections from IGS08 ANTEX files (available via ftp from http://sideshow.jpl.nasa.gov), and corrections for ocean tidal loading (http://holt.oso.chalmers.se). Phase ambiguities were resolved for all the data using GIPSY's single-station ambiguity resolution feature. The no-fiducial station location estimates were transformed to IGS08 using daily seven-parameter Helmert transformations from JPL, thereby yielding daily point-positioned station coordinates that conform to the International Terrestrial Reference Frame 2008 (ITRF08) (Altamimi *et al.* 2011). We applied methods described by Márquez-Azúa and DeMets (2003) to estimate the common-mode noise for stations in southern Mexico and remove it from the position time series. Further details of this procedure are provided in Graham *et al.* (2014a).

2.1.2 *Example GPS Position Time Series*

Figure 3 shows the position time series for two long-operating cGPS sites, one along the Oaxaca segment of the Mexico subduction zone (OAXA/2) and the other along the Guerrero segment (CAYA). The time series highlight obvious differences between the recurrence interval, timing, and relative amplitudes of SSEs along the two segments. At both sites, steady interseismic motion towards the north, representing elastic shortening of the upper North America plate in response to Cocos plate subduction, is interrupted by several-month-long periods of southward motion interpreted as slow slip on the plate interface. Of the six SSEs that occurred between 2005 and 2011, four were recorded at GPS sites in Oaxaca (2005/6, 2007, 2008/9, and 2010/11) and two in Guerrero (2006 and 2009/10) (Fig. 3b). The Guerrero SSEs exhibit longer durations and greater displacements than events in Oaxaca (Fig. 3).

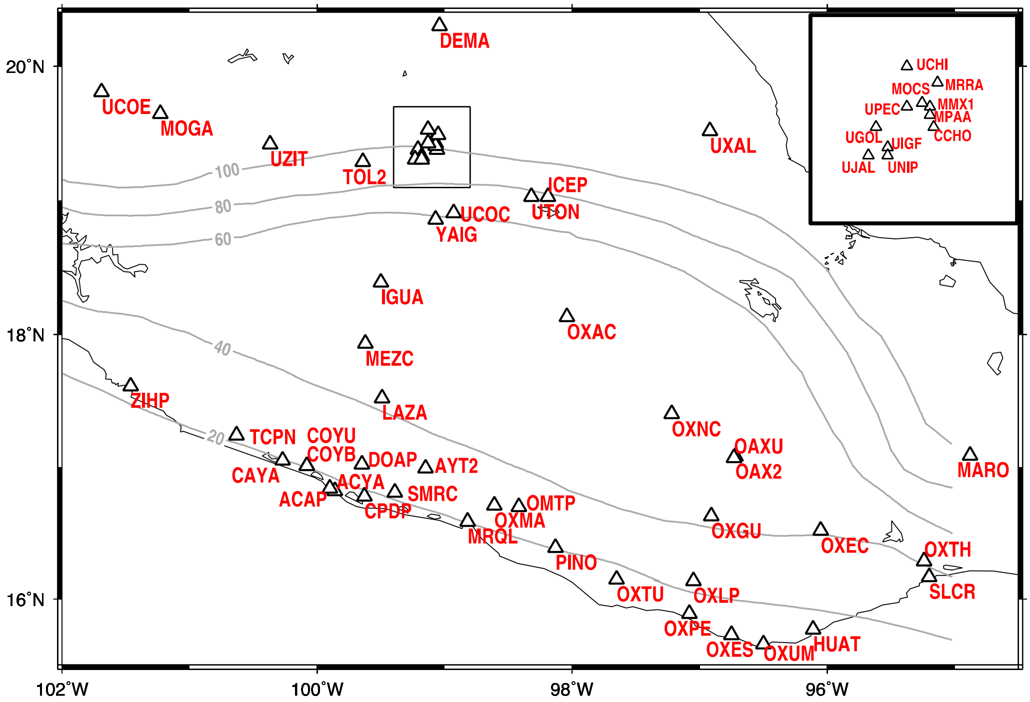


Figure 2
Continuous GPS station locations denoted by *black triangles*. Site names are denoted by their *four-letter* code. *Black rectangle* shows area for *inset*

2.2. Inversion Method: TDEFNODE

We use TDEFNODE (McCaffrey 2009) to invert the cGPS time series to solve simultaneously for the spatial and temporal evolution of slip associated with the six SSEs. In order to isolate the signal of the SSE from the secular interseismic rate at each site, we simultaneously solve for the inter-SSE slope and parameters describing slow slip. Slip is presumed to occur on the subduction zone interface, represented in an elastic half-space using an interface geometry based on depth contours from Radiguet *et al.* (2012). The model space extends along-strike from 94°W to 105°W and from the surface to 80 km depth. Using the Okada (1992) elastic half-space dislocation algorithm, Green's functions are calculated for fault nodes spaced 5 km along-strike and 3 km down-dip. Within the inversion, the spatial slip distribution is estimated at fault nodes with a spread smoothing constraint, where slip is penalized for distance from the slip centroid, and the time evolution of slip-rate per node is modeled with a Gaussian function. Smoothing parameters were adjusted systematically to identify the best tradeoff between the model and data variance. We experimented with other spatial and temporal parameterizations for slip within TDEFNODE, but found that the above combination works best for modeling our data. During the inversion, we estimate the slip-rate amplitude at each node, the nominal event onset time, the rate and azimuth of slip migration, the time constant for the Gaussian function representing slip rate, and the inter-SSE slope. The rake of the slow slip is constrained to be opposite the N32°E direction of Cocos–North America plate convergence (DeMets *et al.* 2010). Further details on our inversion approach are given in Graham *et al.* (2014a).

3. Slow Slip History for 2005 Through 2011

Inversions of data from the 56 continuous GPS sites that were operating in central and southern Mexico from 2005 through 2011 result in spatio-temporal slip distributions for each SSE that are broadly consistent in location, magnitude, and duration with those estimated by previous authors, who used the cumulative SSE offsets to solve for slip (e.g.,

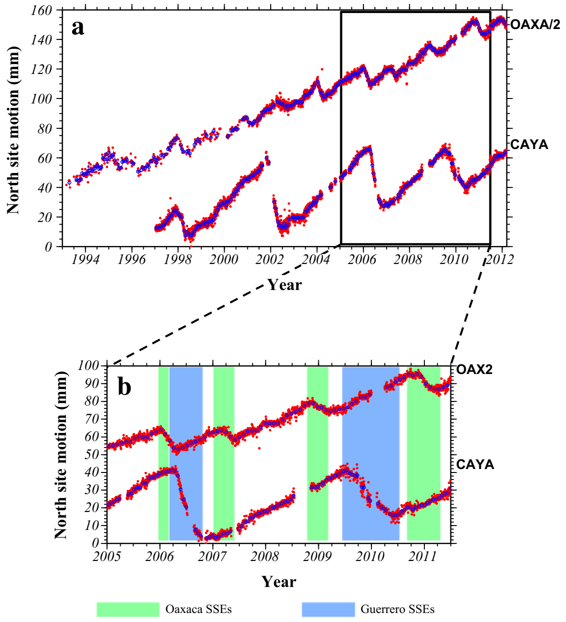


Figure 3

a Complete time series for the north components of cGPS stations in Oaxaca (OAXA/2) and Guerrero (CAYA) reduced by the motion of the North America plate at each site. Site locations are shown in Fig. 2. *Red circles* indicate daily positions and *open blue circles* show 30-day averages. **b** Same as **a**, but for the time period used in this study. *Green* and *blue rectangles* highlight SSEs below Oaxaca and Guerrero, respectively

Correa-Mora *et al.* 2008; Radiguet *et al.* 2011, 2012). For the six events and time series we modeled, the overall weighted root-mean-square (WRMS) misfit to the daily 3-D GPS site positions is 2.4 mm, close to the scatter in the observed daily station positions. The estimated slip on the subduction interface thus captures the north, east, and vertical displacement histories recorded by the cGPS stations.

Table 1 summarizes the main characteristics of the SSEs modeled herein as well as those modeled by other authors covering all SSEs recorded in southern Mexico between 2000 and 2012. The results and time series fits of our inversion for each of the six SSEs are presented below. In addition, we provide in the supplementary material an animation that depicts the slow slip history from 2005 to mid-2011.

3.1. 2005/6 Oaxaca SSE

Slip during the 2005/6 SSE below Oaxaca was focused primarily from 98°W to 97°W and at depths of 20–40 km, with a maximum slip amplitude of 120 mm. Smaller amounts of slip extended ~200 km along-strike (Fig. 4a) and up-dip into seismogenic portions of the subduction zone (Fig. 4a). This slip distribution represents the first evidence that slow slip may extend to shallower depths below Oaxaca than found by Correa-Mora *et al.* (2008). The large displacement of the near-coastal site PINO (located in Fig. 2 and shown in Fig. 4a), data unavailable to Correa-Mora *et al.* (2008), is the key evidence that this SSE extended up-dip to depths as shallow as 15 km. Our modeling suggests that slip migrated slowly up-dip and eastward (N120°E) at a rate of 1.5 km per day (Fig. 5 and supplementary animation). The cumulative geodetic moment for the SSE was 6.0×10^{19} N m ($M_w = 7.1$), the same as estimated by Correa-Mora *et al.* (2008).

The evolution of the surface deformation predicted by our inversion for this SSE matches the GPS position time series at the sites that recorded it (Fig. 6). For example, the position time series for sites PINO, OAX2, OAXU, OXUM, and OXPE are all fit within their observational scatter (Fig. 6). Observations and predicted time series for the entire suite of sites that recorded this SSE are shown in Supplemental Figure A1.

3.2. 2006 Guerrero SSE

Between mid-March and late May of 2006, during the final stages of the 2005/6 SSE below Oaxaca, slow slip began beneath Guerrero ~200 km WNW of the Oaxaca SSE (Fig. 5c). Over a period of 8 months, a region of high slip (~150 mm) migrated southeast towards Oaxaca (Fig. 5c–f), giving rise to cumulative horizontal and vertical surface displacements as high as 50 mm (Figs. 6, A1). The cumulative slip distribution (Fig. 4b) is broadly consistent with both the location and amplitude estimated by Radiguet *et al.* (2012) and the spatio-temporal evolution of slip (local slip duration, migration direction, and speed,) is in very good agreement with that found by Radiguet *et al.* (2011). The majority of slip occurred between 20 and 45 km depth along the plate interface (Figs. 4, 5), with the shallowest slip located in the Guerrero seismic gap (Fig. 4). The peak SSE slip amplitude is 270 mm and the geodetic moment is 10.2×10^{19} N m, equivalent

Table 1

Characteristics of slow slip events (SSEs) along the Mexico subduction zone for the period 2001–2012

SSE	Location along-strike	Location down-dip (km)	Duration in months	Max slip amplitude (mm)	Equivalent magnitude (M_w)	Migration direction	Previous results
2001/02 Guerrero*	~99° to ~101.5°W	20 to 50	9	200	7.65	N/A	Radiguet *et al.* (2012)
2004 Oaxaca*	~97.5° to ~101.5°W	~30	~4	115	7.3	N/A	Correa-Mora *et al.* (2008)
2005/6 Oaxaca	~96.5° to ~98.5°W	−18 to 45	~6	120	7.1	N120E, at 1.5 km/day	CM08: 100 mm max amp, −96° to ~97.75°W, ~22 to 35 km depth; CM09: same location, max amp = 60 mm, $M = 7.1$
2006 Guerrero	~98.5° to ~102°W	20 to 45	~8	270	7.3	N108E	R12: ~99° to ~101°W, −20 to 40 km depth, max amp = 200 mm, $M = 7.5$ Rll: $M = 7.5$,WtoEslip migration, location = R12
2007 Oaxaca	~96.5° to ~97.5°W (centered at 97°W)	Centered at 30	~5	80	6.5	None	CM09: centered at 97°W, depth ~30 km, max amp = 30 mm, $M = 7.0$
2008/9 Oaxaca	~97° to 98.5°W	−30 to 45	~6	120	7.2	N140E, at 4 km/day	N/A
2009/10 Guerrero	−99° to ~102°W	20 to 45	~12	280	7.4	N108E	R12: ~99° to ~101.75°W, −20 to 45 km depth, max amp = 200 mm, $M = 7.53$
2010/11 Oaxaca	−96.75° to ~99°W	Centered at 40	~6	120	7.2	N40W, at 2 km/day	N/A
2011/12 Oaxaca*	~95.5° to ~98°W	20 to 40	5, interrupted byEQ	105	6.9	N36W, at 2.6 km/day	Graham *et al.* (2014a)

CM08 Correa-Mora et al. 2008, *CM09* Correa-Mora et al. (2009), *Rll* Radiguet et al. (2011), *R12* Radiguet et al. (2012), *max amp* maximum amplitude of slip, *EQ* earthquake, *N/A* not applicable

* Results from studies listed in the rightmost column

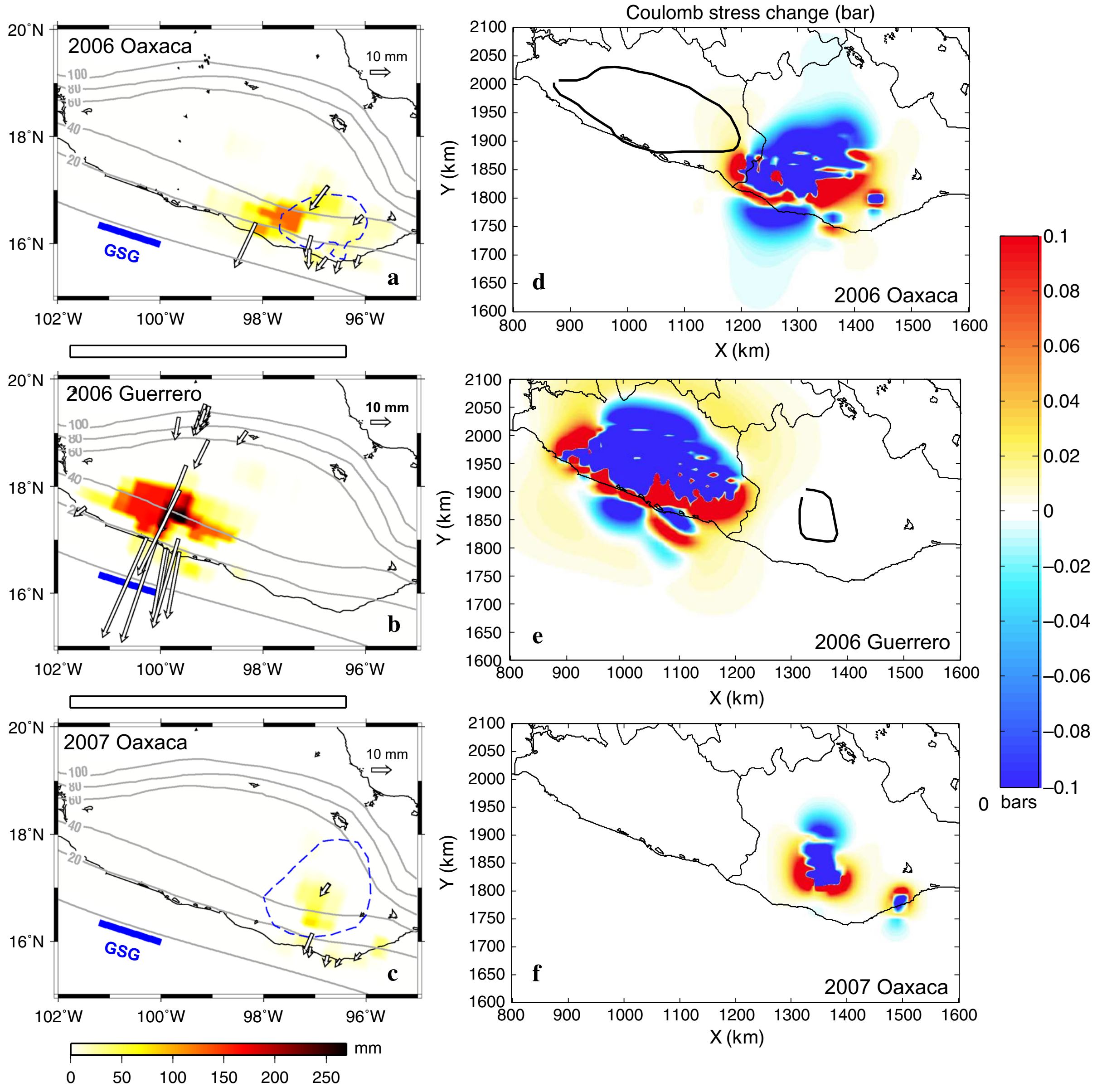


Figure 4

Cumulative slip during the 2005/6 (**a**), 2006 (**b**), and 2007 (**c**) SSEs from time-dependent inversions of the continuous GPS data. *White arrows* show total surface displacements predicted by the modeled slip. *Blue line marks* the along-strike location of the Guerrero seismic gap (GSG). *Blue dash contour* shows slip source for the 2006 (**a**) and 2007 (**c**) Oaxaca SSEs as modeled by Correa-Mora *et al.* (2008, 2009), respectively. **d–e** Coulomb failure stresses calculated from the slow slip for each event. *Black contours* show the location of the subsequent SSE where applicable

to an $M_w = 7.3$ earthquake (Table 1). Slip continued until the onset of the 2007 SSE beneath Oaxaca.

The predicted displacements closely match the observed GPS displacements for the well-recorded 2006 SSE (Fig. 6). Measurements at sites PINO and OXPE, which are located progressively farther eastward along the coast from Guerrero (Fig. 2), clearly show a lack motion during the 2006 Guerrero SSE (Fig. 6). These observations indicate a limit to the eastern extent of the slow slip event.

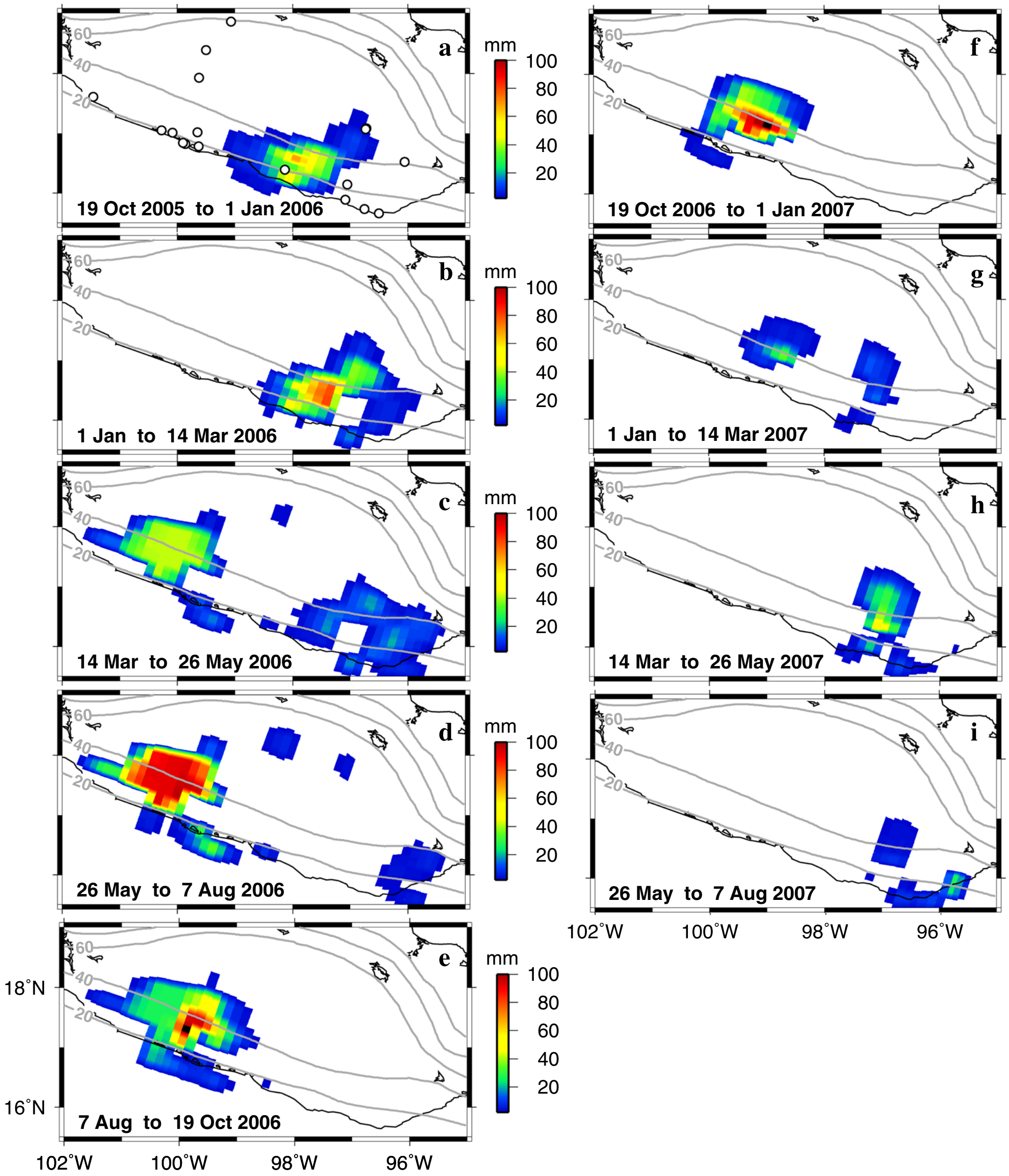


Figure 5

Evolution of slip from 2005 to 2007 at ~2-month-long intervals. The supplementary information includes an animation of the same slip sequence at 2-week-long intervals. The 2006 SSE in Guerrero (**c**–**g**) began during the final stage of slow slip in Oaxaca (**a**–**c**). The eastward-migrating Guerrero SSE is followed in 2007 by a small SSE below Oaxaca (**g**–**i**). The *open circles* in **a** indicate the locations of GPS stations that were used to determine the slip

3.3. 2007 Oaxaca SSE

The smallest SSE detected between 2005 and 2011 occurred below Oaxaca in 2007, ~100 km east of the slip region for the 2006 Guerrero SSE. Relative to the other five SSEs, the 2007 event was smaller in magnitude, spatial extent, and duration (Table 1; Fig. 4). Slip was centered at 97°W and 30 km depth, consistent with previous results (Table 1). The maximum slip amplitude reached 80 mm and the geodetic moment was 5.7×10^{18} N m, equivalent to $M_w = 6.5$. Due to hardware failures and other operational problems, our record of the 2007 SSE is less complete than for the other events. As a result, we cannot resolve with confidence whether there was any geographic or temporal overlap between the 2007 SSE and the waning stages of the 2006 SSE below Guerrero.

3.4. 2008/9 Oaxaca SSE

Between late 2006 and mid-2008, a significant number of new GPS stations were installed between Oaxaca and Guerrero to improve SSE detection. The upgraded cGPS network in southern Mexico detected the onset of slow slip below Oaxaca in October of 2008 following 15 months of uninterrupted inter-SSE elastic shortening in Guerrero and Oaxaca (Fig. 3b). Most slip during the 2008/9 SSE was focused from 30 to 45 km depth (Fig. 7), deeper than the 2005/6 SSE, while slip migrated along-strike (Fig. 8; Table 1). The 2008/9 SSE had nearly the same along-strike location, peak slip amplitude, and geodetic moment as the 2004 and 2005/6 SSEs below Oaxaca (Table 1; Fig. 7a). We note that the difference in the distribution of slip with earlier events could simply be a result of additional stations, particularly those further from the trench (compare GPS displacements in Figs. 4a, 7a). The predicted displacements match the observed cGPS position time series at all the sites (Fig. 9, Supplemental Fig. A2).

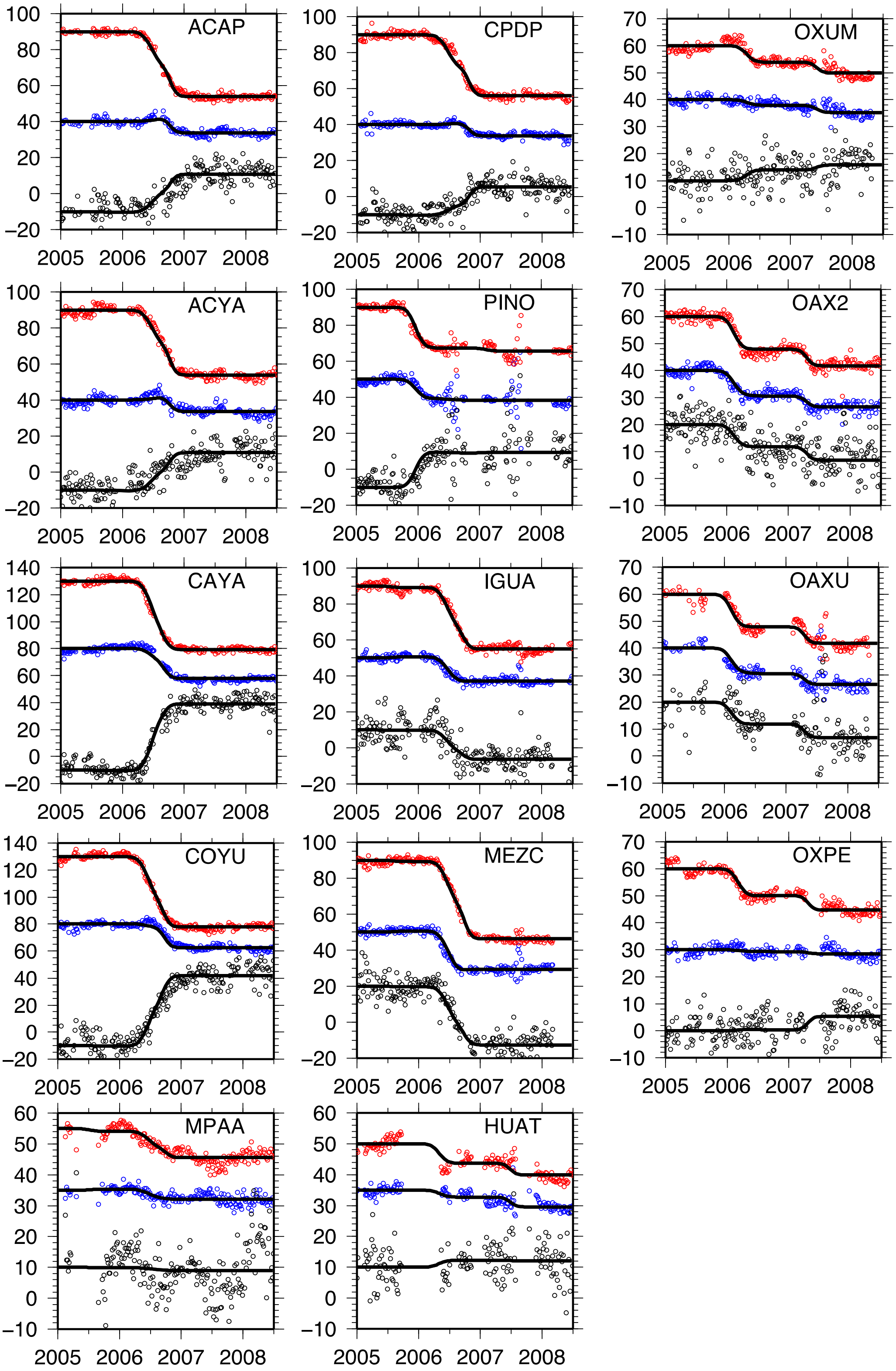
3.5. 2009/10 Guerrero SSE

The 2009/10 SSE below Guerrero was unique with respect to all other SSEs that were previously recorded in southern Mexico in that the GPS time series show two overlapping pulses of deformation, as noted by Walpersdorf *et al.* (2011) (see plots for sites ACAP, ACYA, CAYA, IGUA, and MEZC in Fig. 9). We thus modeled the 2009/10 Guerrero SSE with two sub-events, the second of which began approximately 5 months after the first. Results indicate that the two sub-events are distinct in space and time (Figs. 7, 8d–j). Slip for the first initiated in late May of 2009 (Fig. 8d), increased rapidly in amplitude between late-May and mid-October (Fig. 8e), and diminished through mid-March of 2010 (Fig. 8f, g). Shortly thereafter, the second sub-event began at the eastern end of the earlier sub-event and accommodated as much as 160 mm of cumulative slip before its conclusion in October of 2010 (Figs. 7, 8h–j). The 2009/10 SSE ruptured much of the same part of the plate interface as did the 2006 Guerrero SSE and had similar fault-slip magnitudes (Table 1; Fig. 7). The overall geodetic moment was 12.3×10^{19} N m, equivalent to an $M_w = 7.4$ earthquake.

Using two sub-events, the predicted GPS time series match the observations closely (Fig. 9). If we instead model the SSE as a single event, the two sub-events merge into a single eastward-migrating slow slip event with two high-slip regions. Although the SSE characteristics remain largely unchanged, the time series are fit more poorly. We speculate that the two sub-events are expressions of a single eastward-migrating slow slip event with two high-slip regions (Figs. 7, 8). Modeling by Radiguet *et al.* (2012) of the cumulative, static offsets for the 2009/10 SSE also shows two regions of high slip. The good agreement between our results, which were determined using different modeling techniques and fundamentally different approaches to GPS data processing, suggests that the occurrence of two SSEs in 2009/10 in close proximity in space and time is a robust result.

3.6. 2010/11 Oaxaca SSE

The source region of the 2010/11 Oaxaca SSE was located immediately east of slip during the 2009/10 Guerrero SSE (Fig. 7; Table 1). Slip during this $M_w = 7.2$-equivalent event is remarkably similar to the SSE below Oaxaca in 2008/9 (compare Fig. 7a, d), with the principal difference being that slip in 2010/11 extended ~50 km farther west than in 2008/9 (Fig. 7). Much of the area that slipped in 2008/9 and 2010/11 also slipped during the 2011/12 SSE that preceded the 20 March 2012 $M_w = 7.4$ Ometepec earthquake (Graham *et al.* 2014a), although the 2011/12 SSE appears to have occurred ~5 to 10 km farther up-dip on the subduction interface.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◂ Figure 6
Model fits for selected cGPS stations for the 2006 and 2007 SSEs. *Open circles* are north (*red*), east (*blue*), and vertical (*black*) daily station positions after removing their best-fitting slopes to emphasize the deformation associated with the SSEs. *Black lines* are model predictions

4. *Coulomb failure Stress Changes*

In order to test the hypothesis that stress changes caused by an SSE could trigger subsequent slow slip, we used Coulomb 3.3 (Toda *et al.* 2005; Lin and Stein 2004) to determine the Coulomb failure stress (CFS) changes from the cumulative slip for each SSE at similar depths along the fault. We limited the calculation to fault nodes where the cumulative slow slip exceeded 30 mm, thereby omitting stress variations caused by the more poorly resolved low-slip areas. The effective coefficient of friction was set to 0.4, although changing it to 0.2, corresponding to higher pore-fluid pressures associated at SSE depths, had little impact on the results.

With one exception, our CFS change calculations offer no clear support for the hypothesis that SSEs in Guerroro and Oaxaca trigger SSE elsewhere along-strike (Figs. 4d–f, 7e–h). The predicted CFS changes are all 0.1 bars or smaller except for the first sub-event of the $M_w = 7.4$ 2009/10 Guerrero SSE, which caused up to 1.0 bar of positive CFS change in the source region of the second sub-event (Supplemental Fig. A3). Given that static stress changes as small as 0.1 bars have been correlated with triggered seismicity (King *et al.* 1994), our CFS results are consistent with the possibility that the second sub-event was triggered by the first. Alternatively, Zigone *et al.* (2012) find that seismic waves from the 27 February 2010 Maule earthquake triggered tremor in Guerrero and propose that they also triggered the second sub-event of the 2009/10 Guerrero SSE. Zigone *et al.* (2012) speculate, and our results suggest, that the first sub-event increased the stresses on the region of the second sub-event. That area was subsequently destabilized by the passing seismic waves and evolved into slow slip (Zigone *et al.* 2012).

5. *Mexico Subduction Zone Slip Budget*

Prior to the 20 March 2012 Ometepec earthquake along the MSZ, the deformation measured at GPS sites in southern Mexico for the past decade consisted largely of a superposition of elastic strain that accumulated in the rocks surrounding the seismogenic areas of the plate interface and elastic strain that accumulated in the rocks surrounding deeper portions of the fault, partly relieved by slow slip events every 1–4 years (Fig. 3). Separating these two processes is essential in order to discriminate between strongly coupled areas of the subduction interface that are likely to slip during a future, large thrust earthquake and areas of the plate interface where the interseismic slip deficit and SSE slip may be in balance during the SSE cycle. To accomplish this goal, we combined an independent estimate of the spatial distribution of inter-SSE coupling along the plate interface [Rousset *et al.* (2015) submitted (this volume)] with the SSE slip sources from this study and Correa-Mora *et al.* (2008), as follows.

Along the Guerrero segment, we determined the cumulative slip deficit between July 1, 2002 and October 1, 2010, spanning two complete SSE cycles (i.e. from the end of the 2002 Guerrero SSE to the end of the 2009/10 SSE as shown by Fig. 3), from the product of the 8.25-year length of the time period, the inter-SSE coupling per fault node (Fig. 10c) (Rousset *et al.* 2015) and the Cocos–North America plate convergence rate predicted at each node (DeMets *et al.* 2010). Along the Oaxaca segment, we similarly determined the cumulative inter-SSE slip deficit between October 1, 2002 and May 26, 2011, spanning five complete SSE cycles, from the product of the 9.15-year period (Fig. 3), the inter-SSE coupling distribution from Rousset *et al.* (2015) and Cocos–North America convergence rate per fault node.

To find the slip that was relieved by SSEs during these same intervals, we summed the best-fitting slow slip distributions for the 2006 and 2009/10 SSEs below Guerrero and the 2004 (Correa-Mora *et al.* 2008), 2005/6, 2007, 2008/9, and 2010/11 SSEs below Oaxaca (Fig. 10). Subtracting the accumulated slow slip from the unrelieved slip per fault node gives

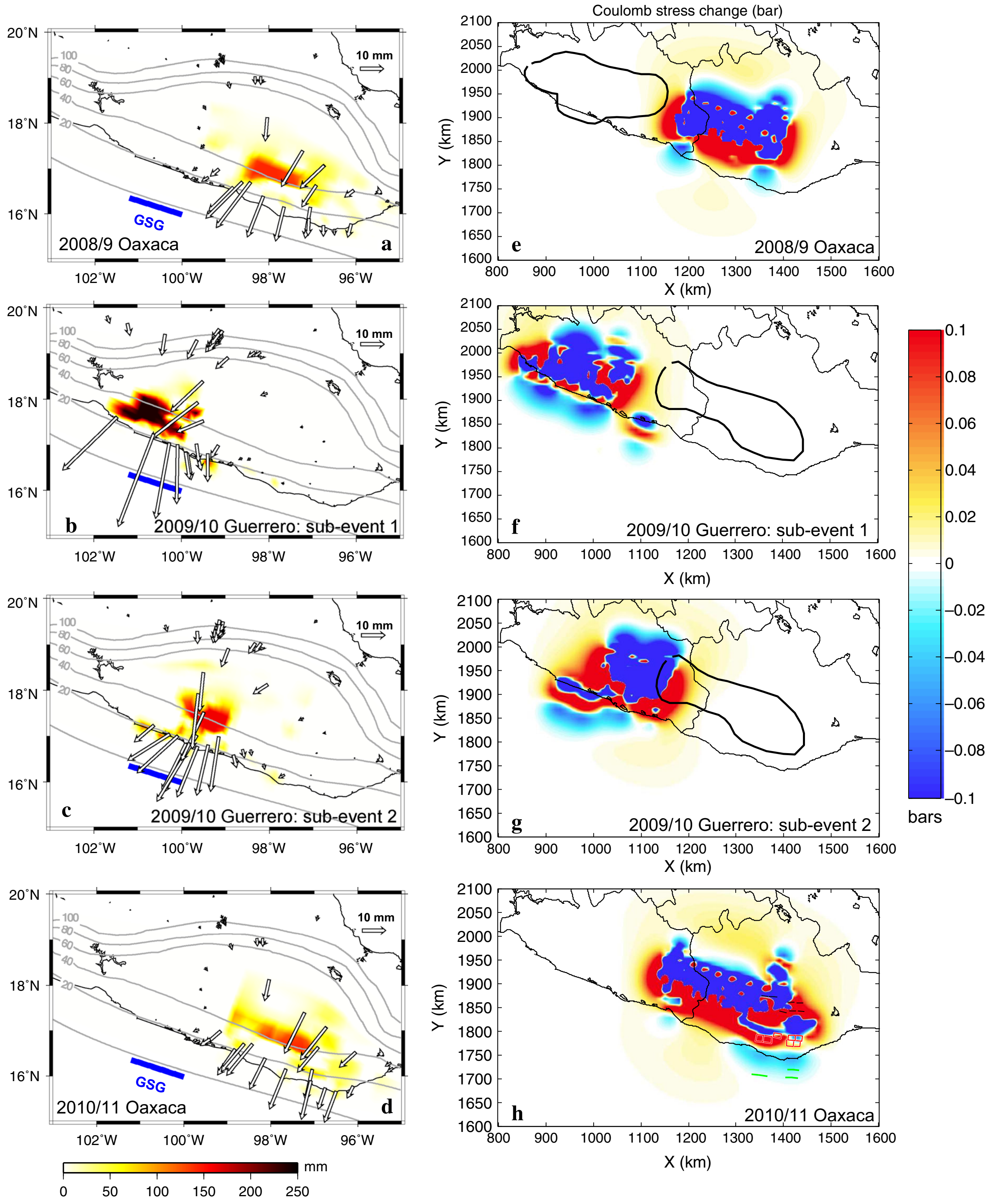


Figure 7

Cumulative slip during the **a** 2008/9, **b**, **c** 2009/10, and **d** 2010/11 SSEs. *White arrows* show surface displacements predicted by the modeled slip. *Blue line* marks the Guerrero seismic gap (GSG). **e**–**h** Coulomb failure stresses calculated from the slow slip for each event. *Black contours* show the location of the subsequent SSE where applicable the distribution of unrelieved fault slip (Fig. 11). This represents our best estimate of where long-term interseismic slip deficit currently accumulates on the Mexico subduction interface. During the past decade, slow slip below Guerrero and Oaxaca not only relieved much of the slip deficit at depths below 20 km in both regions (Fig. 11), but also reduced the slip deficit in the Guerrero seismic gap by up to 75–100 % (Fig. 11). If deformation during the past decade is characteristic of the longer-term deformation, the small remaining slip deficit along the Guerrero seismic gap implies longer recurrence intervals for large earthquakes than for the surrounding areas, in accord with results reported by Radiguet *et al.* (2012).

In Oaxaca, the cumulative slip deficit below 20 km depth was reduced from 200 to ∼0 mm after the cumulative slow slip is removed (Fig. 11). The deep slip deficit that accumulates during the 1–2 years between SSEs is thus approximately balanced by slow slip, in accord with results reported for Oaxaca by Correa-Mora *et al.* (2008). Therefore, little or no slip deficit at depths greater than 20–25 km remains to be released during large earthquakes at the end of a SSE cycle. Slow slip from 2005 through 2011 did not, however, significantly reduce the large slip deficits at shallow depths, particularly near 97°W (Fig. 11), where a strongly coupled portion of the plate interface first identified by Correa-Mora *et al.* (2008) and recently confirmed by Rousset *et al.* (2015) coincides with the 1978 Oaxaca earthquake rupture zone (Fig. 11). These results clearly identify this region as an important seismic hazard area.

6. Discussion

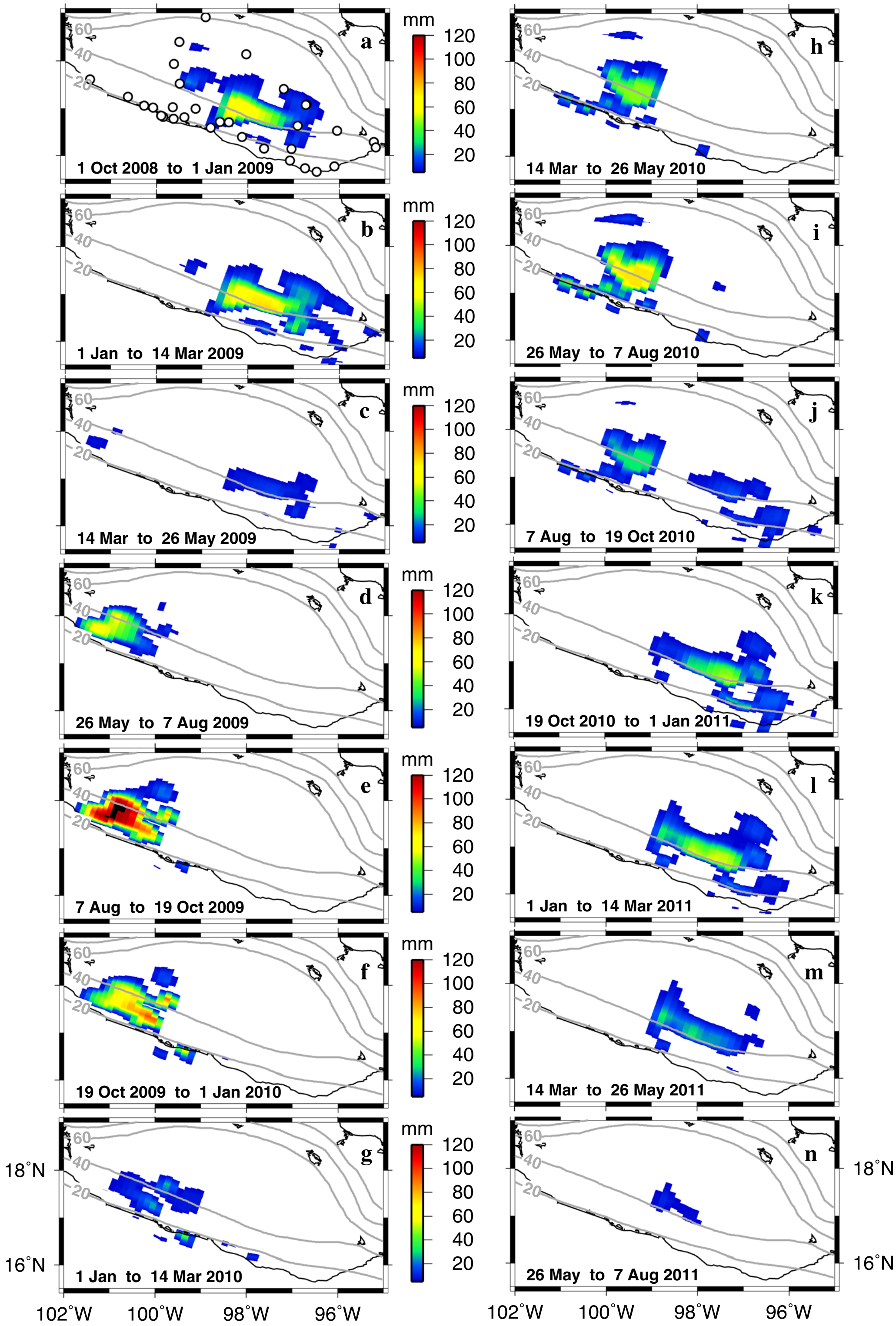
6.1. Comparison to Previous Results

The addition of new GPS stations between 99°W and 98°W since 2005 has improved the GPS network geometry of southern Mexico enough to show that SSEs on the Mexico subduction zone extend everywhere along-strike between Oaxaca and Guerrero. In particular, we find that slip during the previously unstudied 2008/9 and 2010/11 Oaxaca SSEs affected areas of the subduction interface farther west than was estimated for SSEs below Oaxaca in 2004 and 2005/6 (Correa-Mora *et al.* 2009), possibly reaching the source regions of SSE below Guerrero (Fig. 12). In retrospect, the apparent absence of any slow slip between Oaxaca and Guerrero during the 2004 and 2005/6 SSEs (Correa-Mora *et al.* 2009) may have been an artifact of the absence of observations at locations between Oaxaca and Guerrero.

Results for the 2009/10 SSE below Guerrero give slip distributions and slip amplitudes that are consistent with results presented by Radiguet *et al.* (2012), but reveal details of the along-strike migration of the SSE that are missed with static offset modeling. We find that the 2009/10 SSE below Guerrero migrated eastward toward Oaxaca similar to the slip migration of the 2006 event. Observations from the Michoacan segment west of Guerrero, where security problems have precluded the installation of cGPS stations, are needed to determine whether SSEs originate in this region or migrate into it.

6.2. Slow Slip History and the 2012 Ometepec Earthquake

Our modeling adds to evidence described by Graham *et al.* (2014a) that westward-migrating slow slip during the 2011/12 SSE, which originated below central Oaxaca, may have triggered the $M_w = 7.4$ Ometepec earthquake in March of 2012. In particular, Coulomb failure stress calculations (Sect. 4) indicate that the source region for the Ometepec earthquake (located at the intersection of the Oaxaca/Guerrero boarder and the Pacific coast) received positive CFS perturbations from the 2005/6, 2007, and 2008/9 SSEs below Oaxaca (Figs. 4d, f and 7e), the second sub-event of the Guerrero 2009/10 SSE (Fig. 7g), the 2010/11 Oaxaca SSE (Fig. 7h), and the 2011/12 SSE (Graham *et al.* 2014a). Six SSEs in the 6 years preceding the earthquake thus caused static stress changes conducive to fault slip at the down-dip end of the eventual earthquake rupture zone. The combination of a fault segment potentially near failure, steady-state interseismic CFS changes conducive to fault slip, and the 2011/12 SSE that propagated toward the rupture zone in the months preceding the


a
1 Oct 2008 to 1 Jan 2009
b
1 Jan to 14 Mar 2009
c
14 Mar to 26 May 2009
d
26 May to 7 Aug 2009
e
7 Aug to 19 Oct 2009
f
19 Oct 2009 to 1 Jan 2010
g
1 Jan to 14 Mar 2010
h
14 Mar to 26 May 2010
i
26 May to 7 Aug 2010
j
7 Aug to 19 Oct 2010
k
19 Oct 2010 to 1 Jan 2011
l
1 Jan to 14 Mar 2011
m
14 Mar to 26 May 2011
n
26 May to 7 Aug 2011
mm
120
100
80
60
40
20
60
40
20
18°N
16°N
102°W
100°W
98°W
96°W

◀ Figure 8
Evolution of slip from 2008 through 2011 at ~2 month-long intervals. The supplementary information includes an animation of the same slip sequence at 2-week-long intervals. The 2009/10 SSE in Guerrero (**c**–**j**) began during the final stage of slow slip in Oaxaca (**a**–**c**). CFS calculated for the eastward-migrating Guerrero SSE shows positive changes in the source region of the subsequent 2010/11 Oaxaca SSE (**j**–**n**). The *open circles* in **a** indicate locations of GPS stations that were used to determine the slip

earthquake bolster the case that SSE played a role in triggering the 2012 Ometepec earthquake (Graham *et al.* 2014a). Sit (2013) presents evidence for the space–time evolution of microseismicity in the weeks preceding the earthquake that further supports this hypothesis.

6.3. *Seismic Hazard Implications for Widespread Slow Slip*

Our work has several implications for earthquake hazards in southern Mexico. First, the evidence that slow slip in the Guerrero seismic gap reduces the slip deficit at nominally seismogenic depths (Fig. 11), suggests that SSEs below Guerrero likely delay future earthquakes, in accord with results reported by Radiguet *et al.* (2012). Second, the evidence for strong coupling across the 1978 rupture zone offshore from Oaxaca (Fig. 11) accompanied by slow slip events every 1–2 years immediately down-dip from the seismogenic zone argues for increased awareness of the seismic potential of this area during Oaxaca SSEs. Finally, our new evidence for trench-parallel migration of slow slip over distances of 100–200 km implies that Coulomb failure stress changes occur over a broader area than would be the case for the more localized slow slip source regions found by Correa-Mora *et al.* (2009). There are thus more areas in which slow slip could evolve into dynamic rupture, depending on the state of existing stress along the coupled regions of the fault.

6.4. *Comparison to Other Subduction Zones*

Along the Cascadia subduction zone, slow slip and tremor occur at the same depth and location (e.g., Rogers and Dragert 2003; Szeliga *et al.* 2004, 2008; Brudzinski and Allen 2007; Bartlow *et al.* 2011). While in Oaxaca tremor has been noted only at depths below SSEs (Brudzinski *et al.* 2010), observations in Guerrero show two tremor regions (Husker *et al.* 2012). Persistent background tremor has been recorded in a 'sweet-spot' located ~215 km from the trench in the flat slab region of the subduction interface down-dip from the Guerrero SSE region, while intermittent tremor occurs slightly up-dip of the sweet-spot and overlaps the down-dip edge of the SSE slip region (Husker *et al.* 2012; Frank *et al.* 2015). These shallower, intermittent tremor episodes have been associated with short-term SSEs at the limit of detection with GPS (Vergnolle *et al.* 2010; Frank *et al.* 2015). In this respect, SSE and tremor below Guerrero are more similar to those observed in the Bungo channel region of Japan, where tremor is also located both down-dip from long-term SSE slip patches (Hirose and Obara 2005; Hirose *et al.* 2010) and coincides in space and time with short-duration, low magnitude SSEs detected with tiltmeters, but too small to be detected by GPS (Hirose and Obara 2005). It is possible that a similar relationship with shallower tremor bursts and small SSEs may also exist in Oaxaca; however, an investigation into this topic has yet to be conducted.

Our modeling results indicate that slow slip migrates steadily along-strike at rates of 1.5–4 km/day (Table 1) along the subduction zone interface, similar to the 2–15 km/day steady rates observed in Cascadia (Dragert and Wang 2011). In contrast, slip migration of shallow, short-term SSEs in New Zealand can be irregular and patchy, but may include periods during which SSE migrates at rates of 5–9 km/day (Wallace *et al.* 2012). Wallace *et al.* (2012) attribute the irregular migration pattern for New Zealand to the heterogeneity of the shallow portion of the subduction zone interface, where subducted seamounts and surrounding fluid rich sediments may give rise to a complex arrangement of velocity strengthening and velocity weakening fault patches.

Along the Mexico subduction zone, afterslip and SSEs occur at similar depths and afterslip may extend even farther down-dip (Fig. 12) (Graham *et al.* 2014b). Although our modeling results indicate that slow slip has migrated across the region between the Oaxaca and Guerrero segments of the subduction zone, no modeled SSE has yet nucleated in the region

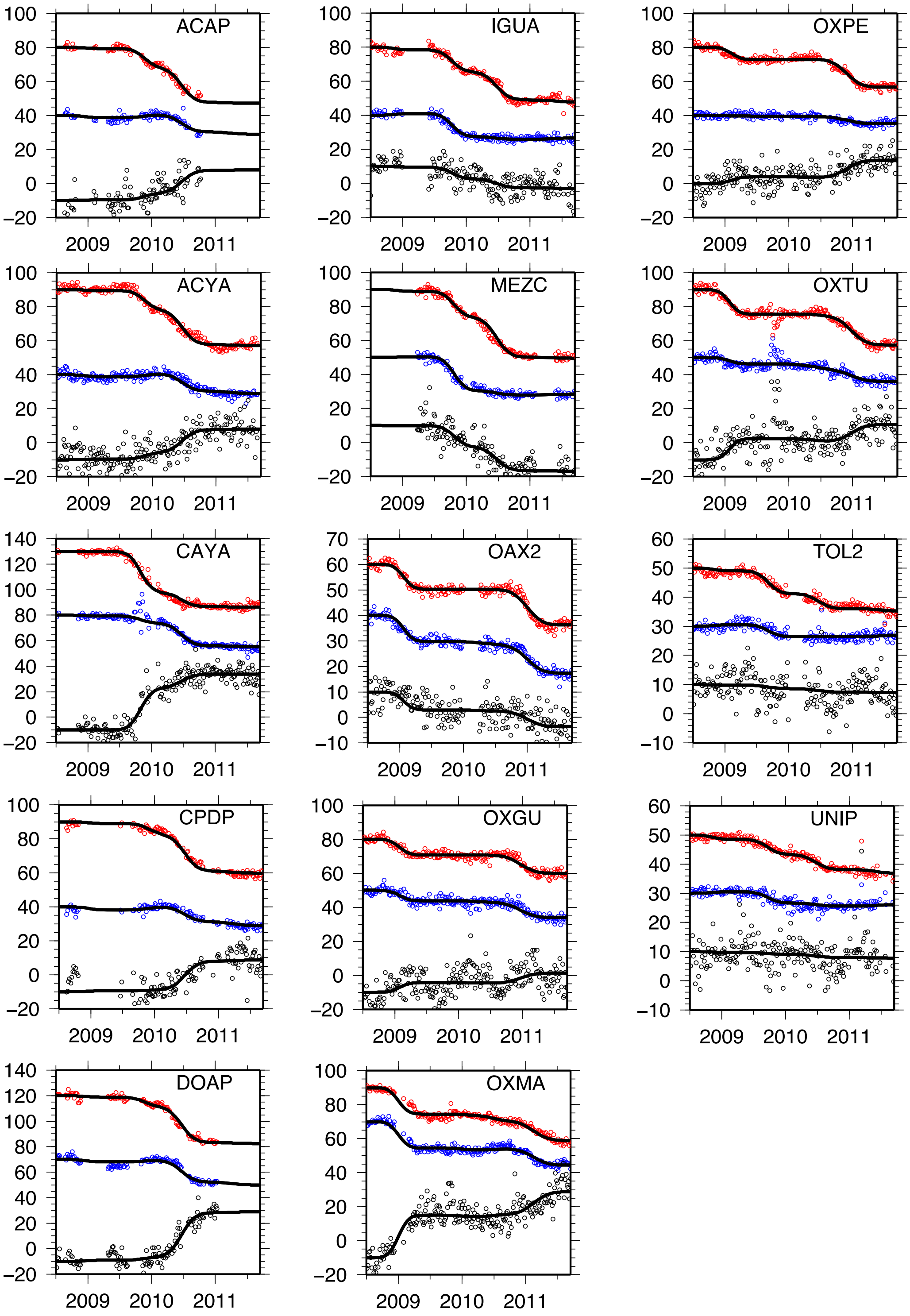


Figure 9

Model fits for selected cGPS stations for the 2008/9, 2009/10, and 2010/11 SSEs. *Open circles* show the north (*red*), east (*blue*), and vertical (*black*) daily station positions after removing their best-fitting slopes to emphasize the deformation associated with the SSEs. *Black lines* are model predictions

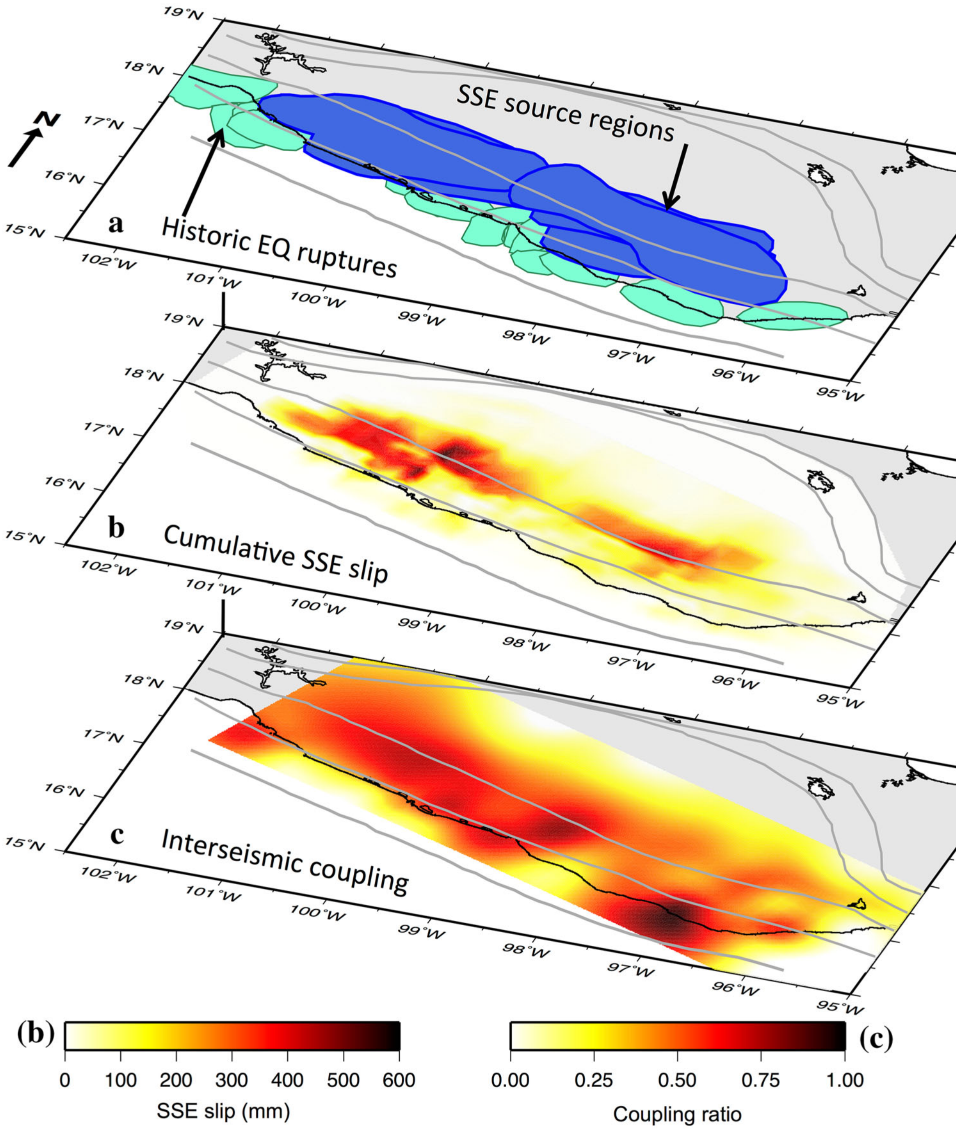


Figure 10

a Historical ruptures (*green*) compared with SSE source regions determined in this study (*blue*). **b** Cumulative slow slip from two complete SSE cycles beneath Guerrero (July 1, 2002–October 1, 2010), which encompasses the 2006 and 2009/10 SSEs, and five complete SSE cycles beneath Oaxaca (October 1, 2002–May 26, 2011) which includes the 2004 (Correa-Mora *et al.* 2008), 2005/6, 2007, 2008/9, 2010/11 SSEs. **c** Inter-SSE coupling determined by Rousset *et al.* (2015). *Gray lines* indicate subduction depth contours from 0 to 80 km depth

between 99°W and 98°W, where large amounts of afterslip followed the 2012 Ometepec earthquake (Graham *et al.* 2014b). Further observations and modeling of SSEs below southern Mexico in 2013 and 2014 are needed to better understand whether the interface in this region differs from the SSE-prone, neighboring regions of the subduction interface or whether the absence of SSE nucleation in this region since the mid-1990s is a merely a time-sampling artifact.

A recent study by Malservisi *et al.* (2015), which modeled the postseismic behavior following the 2012 Nicoya earthquake in Costa Rica, also compares the locations of earthquake afterslip and SSEs. Estimates for afterslip in the 2 years following the earthquake show little to no spatial overlap with the SSE patches

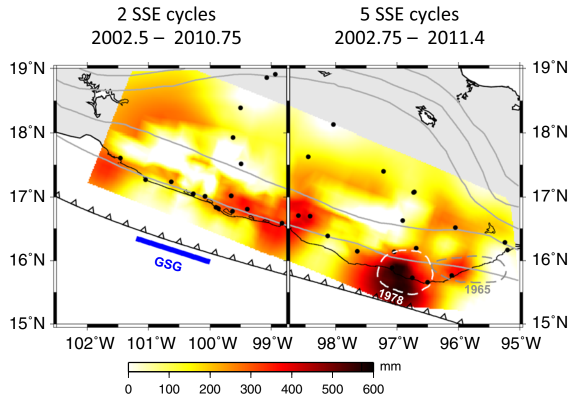


Figure 11
Cumulative fault slip deficit for Guerrero and Oaxaca based on two and five complete SSE cycles, respectively, calculated as described in the text. *Warm colors* represent areas with positive elastic slip deficits, which mark likely seismogenic regions of the plate interface. *Black circles* show GPS stations that were used to estimate the coupling coefficients in Fig. 10. *Gray lines* mark the subduction depth contours at 20 km intervals. *Gray dash* and *white dash contours* indicate the rupture areas for the 1965 and 1978 subduction-thrust earthquakes, respectively

estimated by Dixon *et al.* (2014), thus suggesting a difference in the frictional regimes or driving mechanisms responsible for slip at these locations on the fault (Malservisi *et al.* 2015). Interestingly, along the MSZ, most of the afterslip following the 2012 Ometepec earthquake occurred down-dip from and between the two regions where historically higher amounts of slow slip has occurred (Fig. 12). Whether or not this was coincidental or possible evidence that afterslip is maximized on areas of the subduction interface with larger accumulated slip deficits is unknown. Future studies of afterslip following the recent 18 April 2014 $M = 7.2$ earthquake near the main Guerrero SSE patch might provide useful new information on this topic.

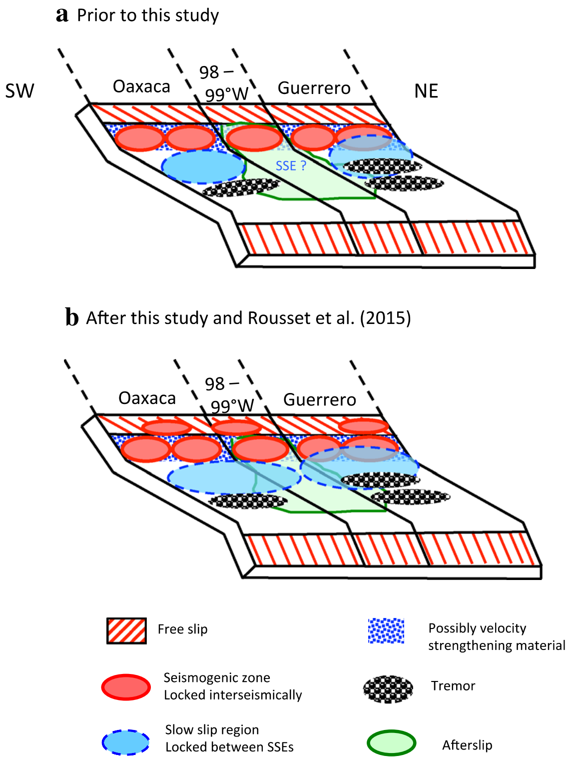


Figure 12
State of knowledge for the Cocos plate portion of the MSZ before (**a**) and after (**b**) this study. Slow slip locations for **a** after Correa-Mora *et al.* (2008, 2009) and Radiguet *et al.* (2012). Slow slip locations in **b** are based on results from this study and shallow interseismically locked patches are from Rousset *et al.* (2015). Afterslip distribution based on afterslip form the 20 March 2012 Ometepec earthquake (Graham *et al.* 2014b). Tremor locations are based on results from Kostoglodov *et al.* (2010) and Brudzinski *et al.* (2010)

7. *Conclusion*

This study presents the first time-dependent modeling of a complete sequence of SSEs along the Mexico subduction zone using an improved GPS network geometry, as well as the first slip models for the 2008/9 and 2010/11 Oaxaca SSEs. We show that slow slip has affected the subduction interface everywhere between Oaxaca and Guerrero, indicating that stress changes from slow slip affect a larger region of the plate interface than was previously known. CFS calculations further suggest that the complex, long-duration slow slip below Guerrero in 2009/10 could have triggered the subsequent SSE below Oaxaca in 2010/11, although independent evidence for causality is absent. Slip estimates indicate that slow slip beneath Guerrero significantly reduces the slip deficit that accumulates across the Guerrero seismic gap, whereas SSEs beneath Oaxaca relieve little or no slip in the strongly coupled seismogenic zone along much of the Oaxaca coastline.

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