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Transient deformation in southern Mexico in 2006 and 2007: Evidence for distinct deep-slip patches beneath Guerrero and Oaxaca

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[1] We model three slow slip events in 2006 and 2007 recorded by continuous GPS stations in central and southern Mexico to test for overlap between their source regions along the Mexican subduction interface and whether they intrude upward into the rupture zones of previous large earthquakes. Inverse modeling yields source regions beneath central Oaxaca for two of the three slow slip events (SSE), where a previously described SSE occurred in 2004, and beneath Guerrero for the third, where slip events previously occurred in 2001–2002 and possibly 1998. Along with previously published results, our work suggests there are persistent differences between the depths and magnitudes of transient slip beneath Oaxaca and Guerrero. Transient slip beneath Oaxaca in 2004, 2006, and 2007 had a common source region downdip from the seismogenic zone and released elastic strain energy equivalent to M_w~7.0 earthquakes, equaling most or all energy that accumulated below the seismogenic zone. Transient slip beneath Guerrero in 2006 had a larger moment magnitude (M_w~7.3) and extended somewhat farther updip, possibly to seismogenic depths. Transient slip thus appears to relieve some elastic strain that accumulates at shallow levels in the Guerrero seismic gap. We find no evidence for spatial or temporal correlations of slow slip along these two widely separated source regions, although better data are needed to test more definitively for any interaction between them.

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1. Introduction

[2] Over the past decade, continuous Global Positioning System (GPS) measurements at station clusters in the states of Guerrero and Oaxaca in southern Mexico have recorded six distinct slow slip events with equivalent elastic strain energy releases of $7 \leq M_w \leq 7.6$ [*Lowry et al.*, 2001; *Kostoglodov et al.*, 2003; *Larson et al.*, 2004; *Brudzinski et al.*, 2007; *Larson et al.*, 2007; *Correa-Mora et al.*, 2008]. The available data clearly establish that transient slip plays an important role in relieving elastic strain energy that accumulates across some parts of the Mexican subduction zone. Much, however, remains to be learned about whether there are significant differences in the depth, magnitude, and frequency of transient slip along the trench, whether there are distinct source regions for the transient slip, and whether transient slip intrudes upward into the seismogenic zone, which for the purpose of this study is defined as the part of the subduction interface that has slipped during previous large subduction thrust earthquakes, as defined from aftershock distributions.

[3] Recent data from new and existing GPS stations in southern Mexico have improved the basis for examining some of these questions. From continuous measurements at 10 stations in the Guerrero region and central Mexico, *Larson et al.* [2007] find that transient slip during the 2006 $M_w = 7.5$ SSE beneath Guerrero appears to have intruded upward into the seismogenic zone, thereby implying that transient slip in this region may relieve at least some of the elastic strain energy that accumulates at shallow depths. In contrast, modeling of SSEs and interseismic velocities recorded by ~30 GPS stations in the state of Oaxaca from 2004 to 2006 suggests that transient slip occurs only below seismogenic depths and thus does not relieve any of the elastic strain energy that accumulates rapidly across the strongly coupled seismogenic zone in this region [*Correa-Mora et al.*, 2008].

[4] Here, we use continuous GPS measurements from stations in southern and central Mexico to better characterize the source regions and characteristics of three SSEs that occurred beneath Guerrero and Oaxaca between July of 2005 and June of 2007 and test for any spatial or temporal connection between these slow slip events. Of particular interest is whether the data hold any evidence that transient slip can migrate long distances (hundreds of kilometers) along the Mexican subduction interface and trigger significant SSEs in regions far from the original source location, as may have occurred for the 2001–2002 slow slip event beneath Guerrero and a small, secondary transient in eastern Oaxaca in 2002 [*Franco et al.*, 2005].

2. GPS Data and Analysis

[5] The data we use consist of continuous measurements from early 2005 to late 2007 from 15 GPS stations in southern and central Mexico (Figure 1). Nine of these sites were installed and are operated by our group for long-term monitoring of the earthquake cycle and volcanic deformation. Six other sites are operated by other agencies or investigators (COYU, CPDP, DOAR OAXA, TOLU, and UNIP). Of these 15 stations, seven are located in coastal areas close to or above seismogenic portions of the subduction zone (Figure 1), three are located ~150 km from the coast above the 30–40 km subduction depth contours, and five are located far inland along the Mexican Volcanic Belt. Our analysis ends in June of 2007 because continuous stations in eastern Oaxaca recorded a transient in the latter half of 2007 with a likely source region east of our network, where too few data are presently available to us to permit reliable modeling of the transient source region and slip distribution.

[6] The GPS coordinate time series for all 15 stations (Figure 2) were determined using a standard precise point-positioning analysis of the raw code phase data [*Zumberge et al.*, 1997] and GIPSY software from the Jet Propulsion Laboratory (JPL). Phase ambiguities are estimated and fixed using AMBIZAP [*Blewitt*, 2006]. Daily station coordinates were estimated in a no-fiducial reference frame [*Heflin et al.*, 1992] and were transformed

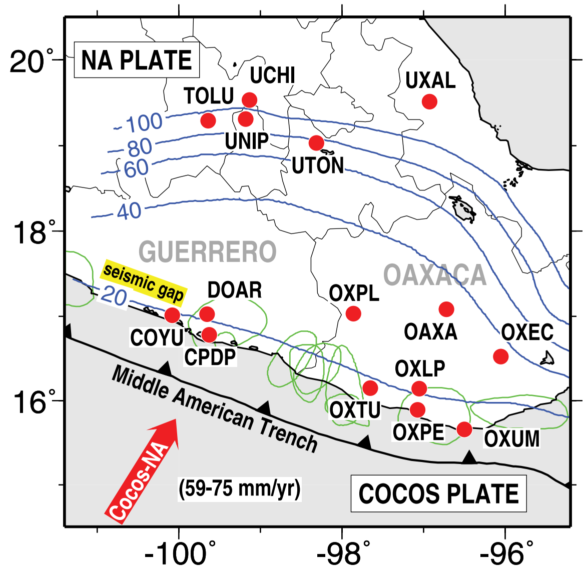

Figure 1. Map of the study area in southern Mexico. Continuous GPS sites are shown by red circles. Green shaded regions along Pacific coast are approximate rupture zones of large subduction thrust earthquakes over the past 50 years from aftershock locations [*Singh et al.*, 1980; *Tajima and McNally*, 1983]. Arrow and parenthetical numerals show Coco-North America plate motion from *DeMets* [2001]. Blue contour lines delineate subduction interface depth contours from *Franco et al.* [2005].

to ITRF2005 [*Altamimi et al.*, 2007] using daily seven-parameter Helmert transformations from JPL. Spatially correlated noise between the daily station coordinates was estimated and removed [*Marquez-Azua and DeMets*, 2003], leaving daily scatter of 1–2 mm and 5–8 mm in the horizontal and vertical components, respectively.

3. Fits to Coordinate Time Series

[7] We begin the analysis by estimating the cumulative offset during each SSE at each of the 15 GPS stations included in the study, thereby defining the pattern of deformation associated with each SSE. Following a brief comparison of their deformation patterns (section 4), we use inverse modeling of the transient offsets for each SSE to identify their optimal source regions and slip distributions (section 5).

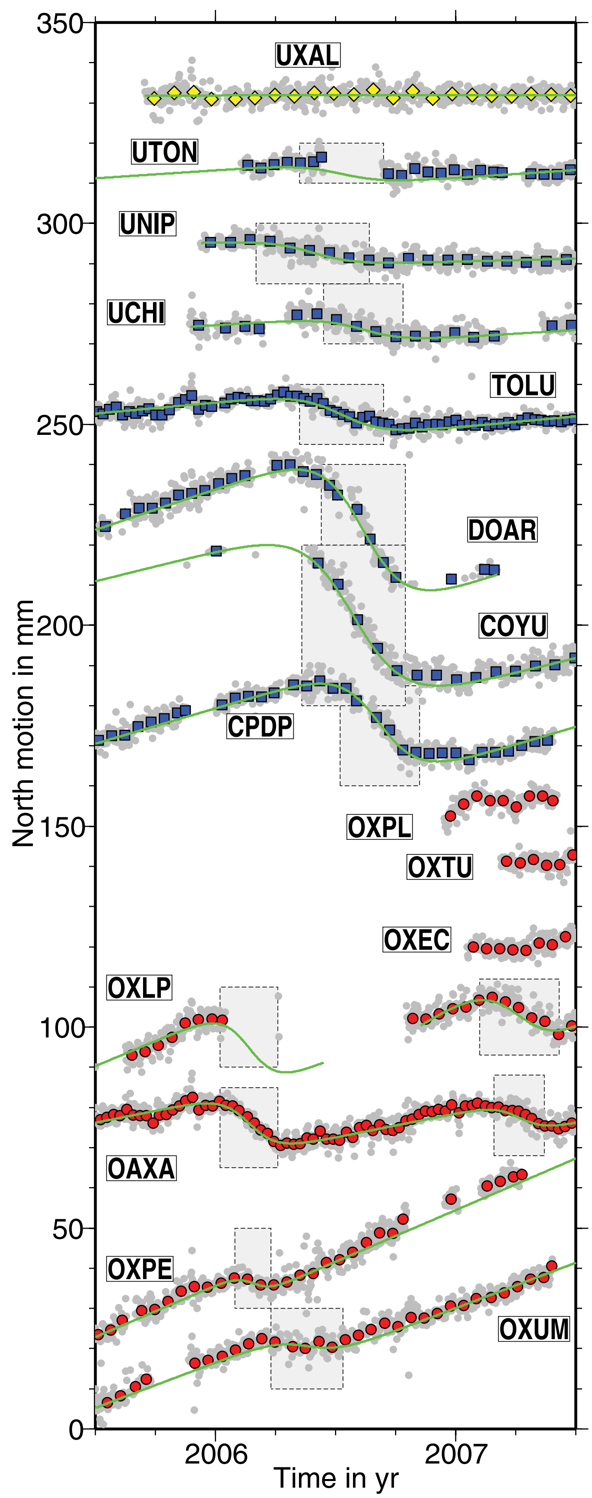

Figure 2. North component of GPS coordinate time series for 15 stations used in the analysis and slip predicted by best-fitting hyperbolic tangent functions (green lines). The motion of the North American plate estimated using GPS stations from the plate interior is removed from each time series. Colored symbols show locations averaged over 10 to 30 days and gray symbols show daily station locations. Time series coded with red symbols indicate stations in and near Oaxaca. Blue symbols indicate stations in Guerrero and the Mexican Volcanic Belt, and yellow symbols are for station UXAL, which lies well inland from the 100-km subduction depth contour. Transient slip events that are determined using the hyperbolic tangent function analysis described in the text are indicated by gray rectangular regions.

[8] Using procedures outlined by *Lowry et al.* [2001] and *Correa-Mora et al.* [2008], we fit each component of the GPS station coordinate time series using a hyperbolic tangent function that includes as adjustable parameters the duration, midpoint, and offset of each transient recorded at that station and the linear station rate. We apply three criteria to determine whether a given time series is adequately fit by its best-fitting hyperbolic tangent function: (1) the root-mean-square fit must be within or close to the scatter in the coordinate time series, (2) the improvement in the least squares fit for the hyperbolic tangent function relative to the fit for a simple linear motion model must pass an F ratio test at the 99% confidence level, and (3) the estimated transient amplitude must exceed 3 mm, our approximate minimum threshold for detecting transient motions. Offsets for GPS stations whose time series fail one or more of these tests are assigned a value of 0 mm and impose useful limits on our inversions for the source region locations and slip distributions.

[9] We use the longest possible data window at each site, including data that fall outside the time window displayed in Figure 2, to estimate the parameters that characterize the best-fitting hyperbolic tangent curve. Uncertainties in the north, east, and vertical components of the transient offset are determined through a rigorous analysis of the tradeoff in the least squares fit between the estimated offset value and the estimated station rate, which are the two parameters that trade off the most when fitting the data. Tradeoffs in the fit between the offset value and other model parameters are typically small and are ignored. Typical 1σ uncertainties range from several millimeters to 10 mm.

[10] All 15 of the GPS time series shown in Figure 2 are fit within their observed scatter by either their best-fitting hyperbolic tangent function or a simple linear motion model. For our inversions of the source region characteristics through time (Figure 3), we used the best-fitting hyperbolic tangent curve at each site to construct a sequence of 30-day station offsets between January of 2006 and late May of 2007. The best-fitting hyperbolic tangent curves implicitly smooth over random variations in the raw coordinate time series and therefore yield less noisy estimates of the sequence of 30-day offsets for each site. Extended Kalman filtering [*McGuire and Segall*, 2003] offers a powerful alternative approach that does not impose a predetermined form on the evolution of transient slip through time; however, we elected not to use it given the good fits of the hyperbolic tangent functions to the data.

4. Comparative Deformation Patterns: Oaxaca and Guerrero

[11] Elastic shortening due to frictional coupling of the Cocos-North America subduction interface along the Pacific coast of Mexico causes GPS stations in most areas of southern Mexico to move ~N25–35°E relative to the interior of the North American plate at rates that decrease with distance from the trench [*Marquez-Azua and DeMets*, 2003; *Yoshioka et al.*, 2004; *Franco et al.*, 2005; *Correa-Mora et al.*, 2008]. Reversals in the directions of stations that are located near the source regions of SSEs are diagnostic of transient slip and are easily recognized in southern Mexico as periods during which station motions are dominated by southward movement.

[12] Fourteen of the 15 GPS stations used in this analysis exhibit one or more periods of south-directed slip between 2006 and mid-2007 (Figures 2 and 3), with total southward offsets that range from ~50 mm for coastal sites COYU and CPDP in Guerrero to only 3–5 mm for sites in the volcanic belt (TOLU, UCHI, UNIP, and UTON). The absence of any interseismic or transient motion in the well-behaved time series for station UXAL (color coded yellow in Figure 2), which is located ~500 km from the trench, indicates that the North

Figure 3. Monthly transient offsets from hyperbolic tangent fits to time series in Figure 2 (blue arrows in the inset maps), predicted offsets (open arrows), and transient slip on the subduction interface that best fits the transient offsets (right). Offset uncertainties are omitted for clarity, but are used to define the best-fitting inverse models. (a) Best inverse models for slip during consecutive 30-day windows beginning 1 January 2006 and ending 27 October 2006. (b) Best inverse models for slip during consecutive 30-day windows beginning 24 February 2007 and ending 24 May 2007. Green circles indicate stations with statistically significant offsets from January to November of 2006 or late February to June of 2007. Red circles indicate stations without statistically significant offsets during either of the above time windows. These stations are assigned offsets of 0 mm. (c) Summed slip for January 2006 to June 2007. White circles show locations of continuous stations that have been installed since May of 2007 in order to better study the migration and location of future SSEs. Profiles A-A', B-B', and C-C' are shown in Figure 5.

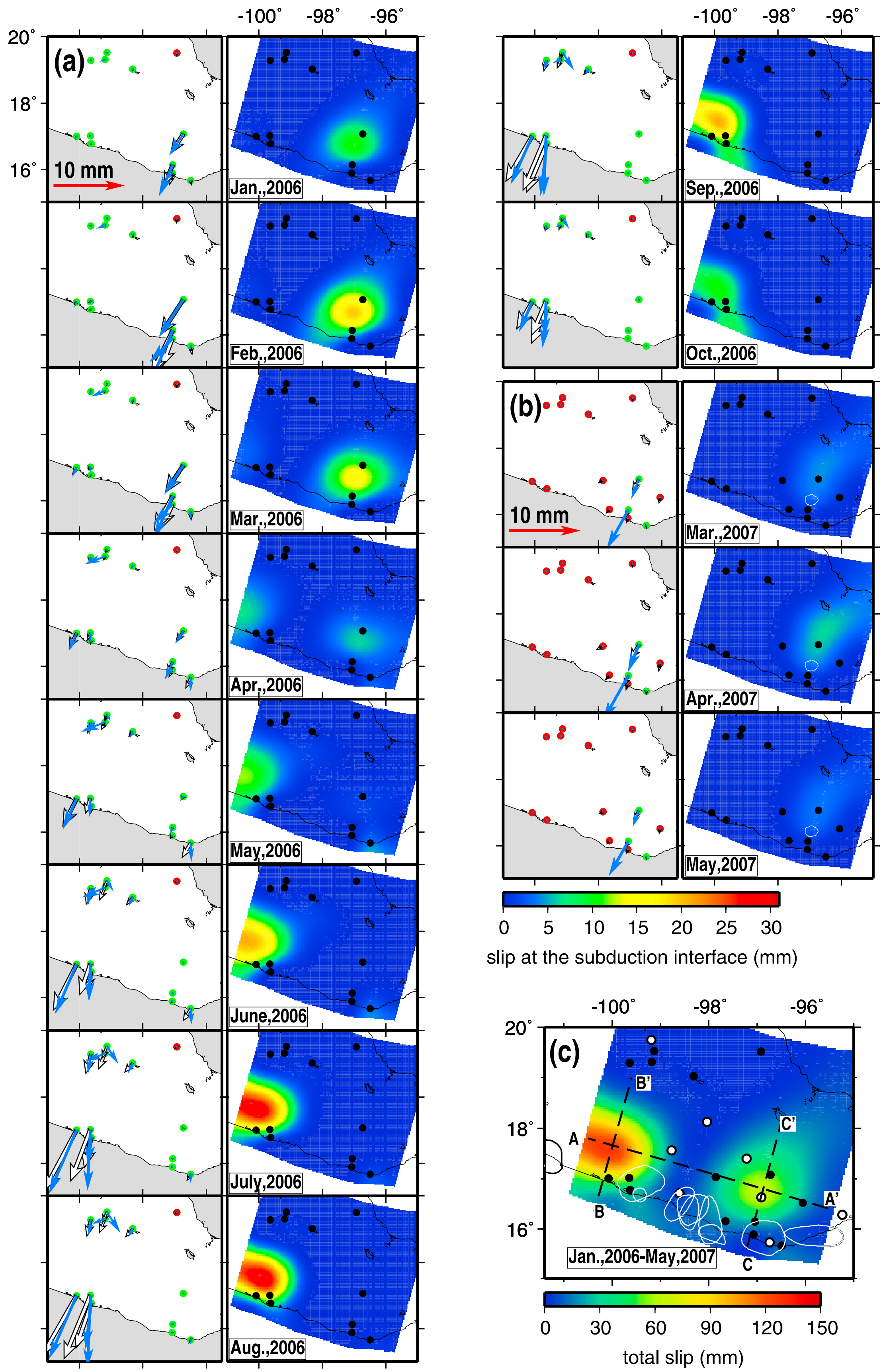
(a)
10 mm
Jan.,2006
Feb.,2006
Mar.,2006
Apr.,2006
May,2006
June,2006
July,2006
Aug.,2006
Sep.,2006
Oct.,2006
(b)
Mar.,2007
Apr.,2007
May,2007
0 5 10 15 20 25 30
slip at the subduction interface (mm)
(c)
Jan.,2006-May,2007
0 30 60 90 120 150
total slip (mm)

Figure 3

American plate reference frame is suitable for describing the motions of sites in southern Mexico and establishes an upper limit of ~2–3 mm for any long-period, nontectonic noise that might affect all of the GPS coordinate time series used here.

[13] The stations can be divided into two groups on the basis of when their motions change. Between April and December of 2006, all but one (UXAL) of the eight stations in Guerrero and the volcanic belt moved southward toward the subduction zone (color coded blue in Figure 2). Their cumulative offsets range from 50 mm for sites along the coast to several millimeters at inland locations, in agreement with similar offsets reported by *Larson et al.* [2007] for some of the same stations.

[14] The second group of stations is located in Oaxaca, where southward, transient station motions occurred twice between January of 2006 and June of 2007 (indicated in Figure 2 by the time series that are colored red). Transient motion from January to May of 2006 was recorded at all four stations operating at the time (OXLP, OAXA, OXPE, and OXUM) and has been described and modeled by *Brudzinski et al.* [2007] and *Correa-Mora et al.* [2008]. A second, previously undescribed SSE that began in February of 2007 was clearly recorded at both of the inland stations in Oaxaca (OAXA and OXLP) but had a negligible effect on the motions of the two coastal sites OXPE and OXUM (Figure 2) and three new stations that began operating in this region in early 2007 (OXEC, OXPL, and OXTU). The five stations that did not record any transient slip nearly encircle the two stations where transient slip was recorded and therefore impose useful constraints in our inversions (described below) on the source region limits for the 2007 SSE.

[15] The patterns of surface deformation recorded in Oaxaca during the January–May 2006 and February–June 2007 SSEs differ significantly from the pattern of deformation that was recorded by sites in Guerrero during the April–December 2006 SSE. In Oaxaca, the offsets at the coastal stations OXPE and OXUM were as much as ~80% smaller than at locations inland (OAXA and OXLP). In contrast, the coastal sites in Guerrero exhibit significantly larger offsets during the April–December 2006 SSE than did the inland stations [*Larson et al.*, 2007]. We next use inversions of the station offsets during all three SSEs to demonstrate that this difference is a likely consequence of a shallower

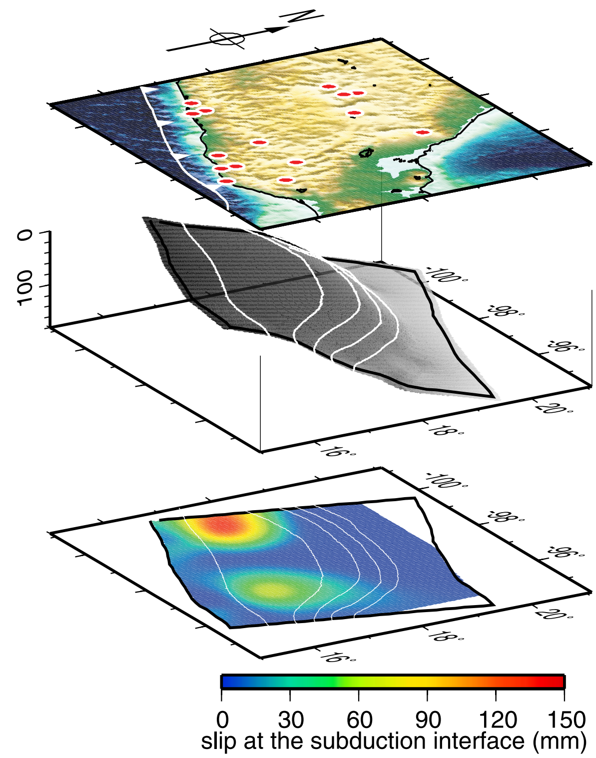

Figure 4. (top) Oblique views of GPS station locations (red circles) within the study area, (middle) the subduction interface embedded in our finite element mesh and its 20 km depth contours, and (bottom) transient slip from Figure 3c.

source region for transient slip beneath Guerrero than for Oaxaca.

5. Transient Slip Source Region Parameters

5.1. Finite Element Mesh and Assumptions

[16] We estimate best-fitting source regions and slip distributions using a three-dimensional, layered finite element mesh that simulates the geometry and properties of the study area and inverse procedures tailored to the problem at hand, as described below. The geometry of the subduction interface embedded in the finite element mesh is adopted from *Franco et al.* [2005], who optimize the interface geometry for the Guerrero and western Oaxaca segments of the subduction zone (Figure 4, middle). We also repeated the modeling using an alternative subduction interface geometry from *Brudzinski et al.* [2007] but without any significant change in results. The elastic properties of the mesh are determined using the CRUST2.0 model from *Bassin et*

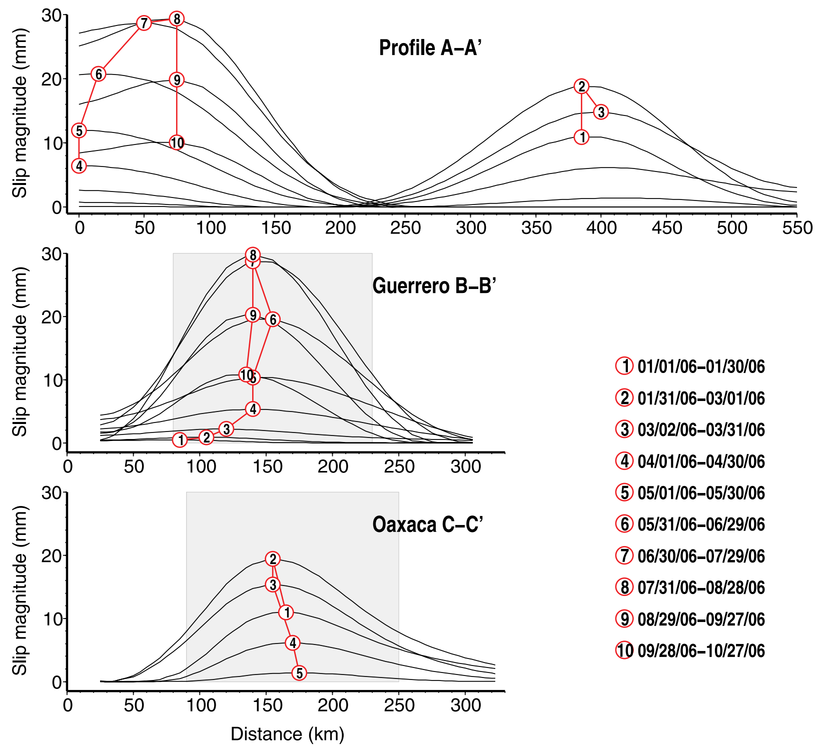

Figure 5. Space-time evolution of transient slip along trench-parallel profile A-A' and trench-normal profiles B-B' in Guerrero and C-C' in Oaxaca (profile locations are shown in Figure 3c). Each line shows 30-day slip amount extracted from the best-fitting slip distributions shown in Figures 3a–3b. Shaded rectangles in profiles B-B' and C-C' indicate areas of the subduction interface that lie between depths of 20 km and 40 km. Circled integers identify the points of maximum transient slip for consecutive 30-day intervals beginning on 1 January 2006.

al. [2000]. Further details about the mesh and its properties, including its boundary constraints and validation procedures, are given by *Correa-Mora et al.* [2008].

[17] Green's functions that are generated from the mesh at the nodes that define the subduction interface form the basis for our inversions of the measured transient offsets. Slip smoothing and uniform sense slip via a nonnegative least squares approach [*Lawson and Hanson*, 1974] are both enforced for all of the inversions. Using procedures described by *Correa-Mora et al.* [2008], we identify and adopt the smoothing coefficient that minimizes reduced χ^2, representing an optimal tradeoff between the degrees of freedom in the model and the model misfit. Each 30-day slip distribution is derived using the same slip constraints and smoothing coefficient (Figure 3ab) so that none of the differences between the slip distributions described below are influenced by changes in the smoothing or other constraints that we use. Further details about the inverse procedures are given by *Correa-Mora et al.* [2008].

5.2. January–May 2006 SSE Beneath Oaxaca

[18] Our inversions of the 30-day offsets measured at all 15 GPS stations define two distinct source regions for transient slip, one beneath the state of Guerrero and the second beneath the state of Oaxaca (Figures 3–5). The source region for transient slip during the January–May 2006 SSE was beneath Oaxaca and was largely limited to depths between 22 and 35 km (Figure 4), in accord with results reported by *Correa-Mora et al.* [2008]. Maximum total slip of ~60 mm occurred ~160–170 km from the trench (Figure 3c and profile C-C' in Figure 5) and the SSE released elastic strain energy equivalent to a M_w = 7.1 earthquake. Both the peak slip amount and elastic strain energy release were significantly smaller than for the M_w = 7.3 SSE in 2004 [*Correa-Mora et al.*, 2008], which had the same source region. Within the uncertainties, no obvious migration of the slip occurred either along strike (profile A-A', Figure 5) or downdip (profile C-C', Figure 5) during this SSE.

[19] The measured transient offsets are well fit by the best-fitting model (compare open and blue arrows in Figure 3a), with root-mean-square misfits of 1.6, 1.3, and 6.7 mm to the north, east, and vertical offsets, respectively. The estimated north, east, and vertical uncertainties are 0.5–1.5, 1.0–1.5, and 2–5 mm, respectively. The data are thus fit at the level of their estimated uncertainties.

5.3. April–December 2006 SSE Beneath Guerrero

[20] The source region for the April–December 2006 SSE (Figures 3a and 5) extended primarily northwest of and downdip from the Guerrero coastal stations, coinciding with the Guerrero seismic gap and an area where intraslab normal faulting earthquakes in early 2006 may have triggered the SSE [*Larson et al.*, 2007]. Our modeling suggests that the source region propagated eastward, parallel to the trench, after May 2006 (profile A-A' in Figure 5), but exhibits no clear evidence for significant updip or downdip migration of the slip (profile B-B' in Figure 5). The source region extends from depths of ~15 km to 40–45 km (Figures 3c–5) and includes peak cumulative slip of ~190 mm at a depth of ~27 km (Figures 3c–5). Most of the slip occurred below the lower limits of historically large earthquakes in this region (Figure 3c); however, several tens of millimeters of cumulative slip are suggested at depths as shallow as 15 km (Figures 4 and 5), within the seismogenic zone. In section 5.5, we examine how well the data resolve this apparently shallow slip.

[21] We also explored whether the GPS offsets for this SSE could be adequately fit by models in which the transient source region was forced to lie east of the Guerrero seismic gap but found that the least squares misfits for such models increased rapidly and significantly for such models. The data thus require that transient slip was focused within the Guerrero seismic gap, with most of the slip occurring at depths below 25 km.

[22] The elastic strain energy release for the Guerrero slip event was equivalent to a $M_w = 7.3$ earthquake, comparable to the M_w ~7.5 estimate of *Larson et al.* [2007] and close to the sizes of previously reported SSEs in this region [*Kostoglodov et al.*, 2003; *Larson et al.*, 2004]. Our modeling results agree with many of the results reported by *Larson et al.* [2007] even though our observations, elastic modeling codes, subduction interface geometries, and techniques for fitting the GPS coordinate time series (hyperbolic tangent versus Kalman filtering) differ.

[23] The offsets measured for this SSE are also well fit by the best-fitting model (open and blue arrows in Figure 3a). The root-mean-square misfits to the north, east, and vertical offsets are 1.2, 2.6, and 8.3 mm, respectively. The estimated north, east, and vertical uncertainties are 0.4–1.0, 0.9–1.4, and 2–4 mm, respectively. The larger misfit to the more poorly constrained east components of the site offsets results from a misfit to the directions of motion at two of the three Guerrero coastal sites (see July, August, and September 2006 panels in Figure 3a), and is a consequence of the smaller uncertainties assigned to the north components in the inverse solution.

5.4. February–June 2007 SSE Beneath Oaxaca

[24] The February–June 2007 SSE recorded at GPS stations in Oaxaca is best fit by slip along a source region beneath Oaxaca (Figure 3b). Neither of the GPS stations that were operating at locations between Guerrero and Oaxaca in early 2007 (OXPL and OXTU) exhibits measurable transient motion during this period (Figure 2), indicating that transient slip beneath Oaxaca in early 2007 did not extend west of ~98°W (Figure 3b). The peak cumulative slip of ~30 mm (Figure 3b) and equivalent moment magnitude of 7.0 for this SSE are both smaller than for the SSE in early 2006, which had peak slip of ~60 mm and an equivalent moment magnitude of 7.1.

[25] The 30-day measured offsets for this SSE are fit more poorly (open and blue arrows in Figure 3b) than are the offsets for the previous two SSEs, with root-mean-squares misfits of 3.1, 3.3, and 11.3 mm to the north, east, and vertical offsets, respectively. In particular, our smoothed solution is unable to fit simultaneously the near-zero (<2 mm) offset recorded at the coastal station OXPE and the 30 ± 7 mm offset measured only 28 km farther inland at site OXLP (Figure 2). The smoothed solution predicts too little motion at OXLP and too much motion at OXPE, representing the best least squares compromise fit given the smoothing imposed on our solution.

[26] We therefore also derived a less smoothed solution to determine whether a model that permits sharper gradients across the edges of the transient source region significantly improves the fit to the offsets at OXLP and OXPE. As expected, transient slip is more concentrated in this model, with a much smaller source region near the updip edge of the smoothed slip patch (shown by the white region in

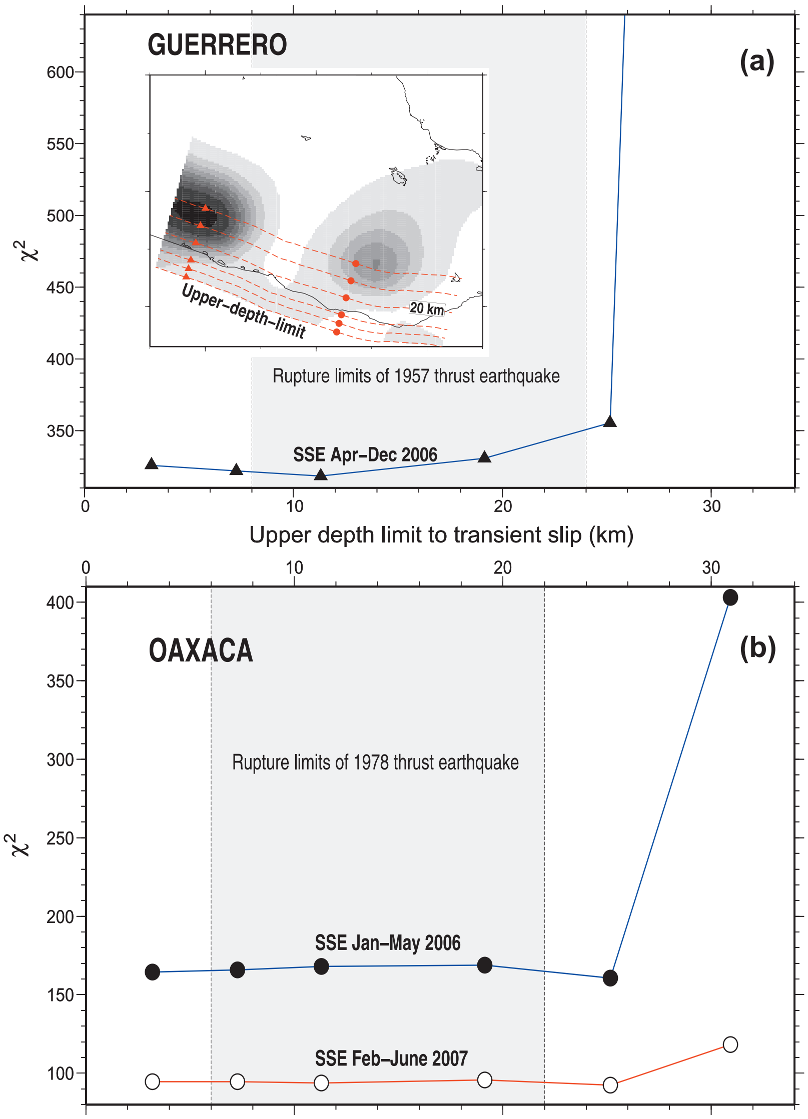

Figure 6. Change in least squares misfit χ^2 for (a) the April–December 2006 SSE in Guerrero and (b) the January–May 2006 SSE and February–June 2007 SSE in Oaxaca as a function of the enforced updip limit to transient slip along the subduction interface. Each symbol shows the misfit when the SSE offsets are reinverted to estimate values of transient slip only for nodes with depths downdip from the designated depth. The slip values for the nodes at or updip from the designated depth are set to zero, thereby confining all transient slip to lower regions of the subduction interface. The same smoothing coefficient is applied for all the inversions. Dashed red lines in the map inset correspond to the depths used for each data reinversion. Fits in Figure 6a become modestly worse if slip is confined below depths of 25 km and dramatically worse if slip is confined below a depth of 31 km. For the SSEs beneath Oaxaca (Figure 6b), no penalty in fit is incurred if slip is confined to depths below 25 km, indicating that the data do not require any slip within the seismogenic zone.

Figure 3b) and a maximum slip value of 200 mm, nearly a factor of seven more than the largest amplitude slip for the more smoothed solution. The RMS misfits for this solution, 2.1, 2.4, and 9.9 mm for the north, east, and vertical offsets, respectively, are smaller than for the more smoothed solution and closer to the RMS misfits for the other two SSEs modeled above.

[27] Despite the differences between the two solutions, both indicate that the 2007 SSE occurred over a significantly smaller area than the SSEs recorded in this region in 2004 and 2006. Both also indicate the source region was located downdip from the seismogenic zone and had a limited extent along strike.

5.5. Does Transient Slip Intrude Updip Into the Seismogenic Zone?

[28] An important question raised by previous studies of SSE in Mexico and elsewhere is whether transient slip intrudes updip into the rupture zones of previous subduction thrust earthquakes. Most relevant to this work, *Yoshioka et al.* [2004] find that models that confine the transient source region of the 2001–2002 SSE beneath Guerrero to depths below 25 km are not able to fit GPS measurements of the surface offsets for that SSE, thereby indicating that some transient slip must have occurred at depths of 25 km and possibly shallower.

[29] In order to establish whether transient slip in 2006 or 2007 extended updip to seismogenic depths, we systematically reinverted the GPS offsets for all three SSEs described above to determine how the model fits vary as a function of the enforced updip (shallow) limit for any estimated transient slip. For a series of assumed depths that correspond to the node rows in our finite element model (shown by the red dashed lines in Figure 6), we reinverted the GPS offsets for each SSE to estimate slip values only for the nodes located downdip from the selected depth. The GPS data are thus fit by a series of models in which the transient source region is confined to progressively deeper areas of the subduction interface.

[30] For the April–December 2006 SSE beneath Guerrero (Figure 6a), the fits differ insignificantly for models in which the shallow depth limits for transient slip are set to 3 km, 7 km, or 11 km. There is thus no penalty in the fit for models in which transient slip is confined to depths below 11 km. Models in which the updip limit for transient slip coincides with the nodes at depths of 12 km or 19 km fit the data more poorly, though insignificantly so (a few percent). The data thus do not strongly require slip at depths of 19 km or shallower, at potentially seismogenic depths, but are less consistent with such models. The misfit for a model in which no slip is permitted at depths of 25 km or shallower is ~10% worse than for the best model and increases dramatically if we further confine the source region to areas below depths of 31 km. The data thus require that the nodes at depths of 31 km accommodate significant transient slip.

[31] Given the depth-spacing between the adjacent node rows in our FEM, we cannot preclude significant slip at depths as shallow as 26 km, indistinguishably different from the lower limit of the seismogenic zone. Our evidence for significant slip to depths of at least 31 km concurs with conclusions reached previously by *Yoshioka et al.* [2004] based on observations of the 2001–2002 Guerrero SSE, namely, that significant slip occurs at depths as shallow as 25 km. Our model does not preclude additional shallower slip, possibly as large as 30 mm at depths of only 15 km; however, our analysis indicates that our ability to resolve such slip is limited by the few data used for our inversion.

[32] We did not estimate what constitutes a significantly worse fit for these alternative models because nearly all the information is supplied by the velocities for the three coastal stations in Guerrero, too few for a reliable statistical test. Additional observations such as those published by *Larson et al.* [2007] are needed for a stronger test.

[33] We repeated the same procedure to determine the updip limits for the 2006 and 2007 SSEs beneath Oaxaca (Figure 6b). For the January–May 2006 SSE, the GPS offsets are equally well fit by models that permit slip to extend all the way to the surface or instead confine the source region to depths below 25 km. No slip is thus required in the seismogenic zone. The misfit however increases by nearly a factor of three if the source region is confined to depths below 31 km, indicating that slip is strongly required for the nodes at a depth of 31 km. Similar changes occur in the misfit for the 2007 SSE site offsets (Figure 6b), although the changes in fit are less dramatic due to the smaller signal-to-noise ratio for this SSE. In conclusion, there is no penalty in the fits for models that confine the source regions for the SSEs beneath Oaxaca in 2006 and 2007 to depths downdip from the seismogenic zone.

6. Discussion

[34] Our modeling indicates that the January–May 2006 and February–June 2007 SSEs both had source regions beneath central Oaxaca, coinciding with the previously reported source region of the SSE that was recorded in this region in 2004 [*Brudzinski et al.*, 2007; *Correa-Mora et al.*, 2008]. The 2004, 2006, and 2007 SSEs beneath Oaxaca occurred at depths below the seismogenic zone and had equivalent moment magnitudes of 7.0–7.3. The available data do not indicate that significant migration of the SSE occurred along-strike, updip, or downdip in either 2006 or 2007. These two transients continue a pattern described by *Correa-Mora et al.* [2008] whereby transient slip beneath Oaxaca repeats every 1–2 years, lasts ~3 months, does not extend upward into the seismogenic zone, and relieves most or possibly all of

the elastic strain energy that accumulates downdip from the seismogenic zone. Neither the continuous GPS data in Oaxaca nor Guerrero support the existence of annual SSE, as suggested by *Lowry* [2006].

[35] In contrast to the characteristics of SSEs beneath Oaxaca, transient slip in Guerrero has consisted of large events in 1995 (M_w = 7.1), 1998 (M_w = 7.1), 2002 (M_w = 7.6), and 2006 (M_w = 7.3–7.5) [*Lowry et al.*, 2001; *Kostoglodov et al.*, 2003; *Iglesias et al.*, 2004; *Larson et al.*, 2004; *Yoshioka et al.*, 2004; *Franco et al.*, 2005; *Larson et al.*, 2007]. From modeling of ten continuous GPS stations in Guerrero, *Larson et al.* [2007] finds evidence that transient slip occurred within the seismogenic zone in 2006; however, it is unclear from that analysis whether such slip is well resolved. Our own modeling, based on fitting fewer observations from Guerrero, also suggests that some slip extended to depths of 25 km, although the misfit penalty is only 10% for models that instead confine the transient source region to depths of 31 km or lower. Modeling of the 2001–2002 SSE, which was recorded by fewer GPS stations, suggests that transient slip extended updip to at least 25 km [*Yoshioka et al.*, 2004], consistent with our results (Figure 6a). The question of whether significant transient slip extends to depths as shallow as 10–15 km in the Guerrero seismic gap is thus, in our view, still unresolved.

[36] The available evidence indicates that the April–December 2006 SSE beneath Guerrero was distinct in space and time from the January–May 2006 and February–June 2007 SSEs beneath Oaxaca. The source region for the Guerrero SSE was separated by at least ~100 km from the source regions for both SSEs beneath Oaxaca (Figures 3c, 4, and 5). Moreover, the pattern of surface deformation in Guerrero, where more transient deformation occurs along the coast than inland, is consistent with shallower and larger magnitude transient slip beneath Guerrero than beneath Oaxaca, where the largest transient deformation instead occurs at inland locations. The lack of surface deformation at two stations (OXPL and OXTU) that were operating between Oaxaca and Guerrero in early 2007 indicates that transient slip along the subduction interface did not migrate west from central Oaxaca toward Guerrero during the 2007 SSE (Figure 3b). Evidence for transient deformation that began in July of 2007 from recently recovered observations at stations OXEC and OXUM at the eastern edge of our continuous network suggest that the February–May 2007 SSE may have migrated slowly to the east in the latter half of 2007. This remains a topic of future study.

[37] Our analysis suggests that at least two independent SSE source regions lie beneath southern Mexico. Significantly denser station coverage is however needed for a strong test of whether transient slip that originates in one source region can propagate hundreds of kilometers along strike and possibly trigger a later SSE in another source region, as may have been the case in 2001–2002 [*Franco et al.*, 2005]. An ongoing, multi-institutional densification of continuously operating GPS and seismic stations in southern Mexico, including six continuous GPS stations that we recently installed south of the Mexican Volcanic Belt (white circles in Figure 3c) and continuous broadband seismic stations we are operating at most of these sites, should significantly enhance future estimates of source region parameters for SSEs in southern Mexico.

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