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

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We model three slow slip events recorded in 2006 and 2007 by continuous GPS stations in central and southern Mexico to test whether they have a common source region along the Mexican subduction interface. Inverse modeling of the two slow slip events in early 2006 and 2007 yields source regions beneath central Oaxaca, where a previously described slow slip event occurred in 2004. Transient offsets from June to December of 2006 instead originated beneath Guerrero, coinciding with the source regions of slip events recorded in Guerrero in 2002 and possibly 1998. Along with previously published results, our work reveals 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 energy equivalent to $M_w \sim 7.0$ earthquakes, equaling most or all energy that accumulated below the seismogenic zone. Transient slip beneath Guerrero in 2006 had a larger moment magnitude ($M_w \sim 7.3$) and extended updip to seismogenic depths of 15 km, as may also have occurred during the more sparsely recorded 2001/2002 slow slip event in Guerrero. Transient slip thus relieves 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 from 2004 to 2007, although better data are needed to test more definitively for any interaction between the two source regions.

1. Introduction

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 (SSE) with equivalent elastic 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 energy that accumulates across some parts of the Mexican subduction zone. Much however remains to be learned about whether transient slip intrudes upward into the seismogenic zone, whether there are significant differences in the depth, magnitude, and frequency of transient slip along the trench, and whether there are distinct source regions for the transient slip.

Recent data from new and existing GPS stations in southern Mexico have improved the basis for examining some of these questions. *Larson et al.* [2007] employ continuous measurements from 10 stations in the Guerrero region and central Mexico to demonstrate that transient slip during the 2006 M_w=7.5 SSE beneath Guerrero intruded upward into the seismogenic zone, thereby implying that transient slip in this region relieves at least some of the elastic 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 indicates that transient slip occurs only below seismogenic depths and thus does not relieve any of the elastic energy that accumulates rapidly across the strongly coupled seismogenic zone in this region [*Correa-Mora et al.*, 2008].

Here, we use continuous GPS measurements from stations in southern Mexico from late 2005 to June of 2007 to better characterize the source regions and characteristics of three SSEs that occurred beneath Guerrero and Oaxaca during this period 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 remote from the original source region, as may have occurred for the 2001/2002 slow slip event beneath Guerrero and a small, secondary transient in eastern Oaxaca [*Franco et al.*, 2005].

2. GPS data and analysis

The data we use consist of continuous measurements from 15 GPS stations in southern and central Mexico (Fig. 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 (Fig. 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.

The GPS coordinate time series for all 15 stations (Fig. 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 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. Comparative deformation patterns: Oaxaca and Guerrero

Elastic shortening that accompanies 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^{o}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.

Fourteen of the fifteen GPS stations used in this analysis exhibit one or more periods of south-directed slip between 2006 and mid-2007 (Figs. 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, UTON and UXAL). The absence of any interseismic or transient motion in the well-behaved time series for station UXAL (color coded yellow in Fig. 2), which is located ~500 km from the trench, indicates that the North 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, non-tectonic noise that might affect all of the GPS coordinate time series used here.

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 Fig. 2). Their cumulative offsets range from 50 mm for sites along the coast to several mm at inland locations, in agreement with similar offsets reported by *Larson et al.* [2007] for some of the same stations.

The second group of stations are located in Oaxaca, where southward, transient station motions occurred twice between January of 2006 and June of 2007 (indicated in Fig. 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 (Fig. 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.

The patterns of surface deformation recorded in Oaxaca in both early 2006 and early 2007 differ significantly from the pattern of deformation that was recorded by sites in

Guerrero in mid-2006. 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 2006 SSE than did the inland stations [Larson *et al.* 2007]. Below, we demonstrate that this difference is a consequence of a significantly shallower source region for transient slip beneath Guerrero than for Oaxaca.

4. Fits to coordinate time series

Our modeling objectives are to estimate the optimal source regions and slip distributions through time for each of the transients described above. We first use the coordinate time series for each GPS site to determine station offsets during consecutive 30-day windows from January 1, 2006 to May 26, 2007 (Figs. 3ab). We then invert the offsets for each 30-day window to find its corresponding source region and slip distribution (Figs. 3ab) and sum these to determine the cumulative source regions and slip distributions (Fig. 3c). Each step is described briefly below.

Following procedures outlined by *Lowry et al.* [2001] and *Correa-Mora et al.* [2008], we use a hyperbolic tangent function to determine the duration, mid-point, and offset that yield the best least-squares fit for each SSE that is recorded at each GPS station. We apply three criteria to determine whether a given time series is adequately fit by a hyperbolic tangent function: 1) the root-mean-square fit must be within or close to the scatter in the 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 zero mm and impose useful limits on our inversions for the source region locations and slip distributions.

All transient offset uncertainties are determined through a rigorous analysis of the trade-off in the least-squares fit between the estimated offset value and station velocity. Trade-offs in the fit between the offset value and other model parameters are typically small and are ignored. Typical 1σ uncertainties range from several mm to 10 mm.

All 15 of the GPS time series shown in Fig. 2 are fit within their observed scatter by either their best-fitting hyperbolic tangent function or a simple linear motion model. Given the good fit, we used the best-fitting hyperbolic tangent curve for the sites that satisfy the three criteria outlined above to find their corresponding sequence of 30-day offsets between January of 2006 and late May of 2007 (Fig. 3ab). 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. Although extended Kalman filtering [*McGuire and Segall*, 2003] offers a powerful alternative approach that does not impose a pre-determined form on the evolution of transient slip through time, we elected not to use it given the good fits of the hyperbolic tangent functions to the data.

5. Transient slip source region parameters

We estimate the best-fitting source region locations and slip distributions using an inverse procedure and three-dimensional, layered finite element mesh that incorporates a subduction interface from *Franco et al.* [2005], who optimize the interface geometry for the Guerrero and western Oaxaca segments of the subduction zone (middle panel of Fig. 4). Details regarding the mesh, its properties, and the inverse procedures used to derive the best-fitting solutions are given by *Correa-Mora et al.* [2008] and are only summarized below. We also repeated the modeling described below using the subduction interface geometry from *Brudzinski et al.* [2007]. Both give similar results.

The elastic properties of the mesh are determined using the CRUST2.0 model from *Bassin et al.* [2000]. Green's functions generated from the mesh at the nodes that define the subduction interface form the basis for the data inversion. Slip smoothing and uniform-sense slip via a non-negative least-squares approach [*Lawson and Hanson*, 1974] are both enforced uniformly 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 (Fig. 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.

Our inversions of the 30-day offsets define two distinct source regions for transient slip, one beneath the state of Guerrero and the second beneath the state of Oaxaca (Figs. 3-5). The source region for transient slip from January to May of 2006 was beneath Oaxaca and was largely limited to depths between 22 and 35 km (Fig. 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 ((Fig. 3c and profile C-C' in Fig. 5) and the SSE released elastic energy equivalent to a M_w=7.1 earthquake. Both the peak slip amount and elastic 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', Fig. 5) or downdip (profile C-C', Fig. 5) during this SSE.

Transient slip beneath Guerrero began in early April of 2006 (Figs. 3a and 5) and continued into December of 2006. The source region extended primarily northwest of and downdip from the Guerrero coastal stations, in an area where intra-slab normal faulting earthquakes that occurred in early 2006 may have triggered the transient [Larson *et al.* 2007]. The source region propagated to the east parallel to the trench after May 2006 (profile A-A' in Fig. 5), consistent with the eastward progression of slip described by Larson *et al.* [2007]. There is however no clear evidence for significant updip or downdip migration of the slip (profile B-B' in Fig. 5). The source depths extend from ~15 km to 40-45 km (Figs. 3c-5) and include peak cumulative slip of ~190 mm at a depth of ~27 km (Figs. 3c-5). Most of the slip occurred below the seismogenic depth limit in this region; however, ~50 mm of cumulative slip is required at a depth of 15 km (Figs. 4 and 5), within the seismogenic zone, to fit the relatively large transient offsets that occurred at coastal sites in Guerrero.

The elastic energy release for the Guerrero slip event was equivalent to a M_w=7.3 earthquake, comparable to 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 recursive Kalman filtering) differ.

The transient motion that was recorded at GPS stations in Oaxaca between late February and May of 2007 is best fit by slip along a source region beneath Oaxaca (Fig. 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 (Fig. 2), indicating that transient slip beneath Oaxaca in early 2007 did not extend west of $\sim 98^o$W (Fig. 3b). The western limit of the source region for the 2007 SSE is comparable to those estimated for the more sparsely recorded 2004 and 2006 SSEs beneath Oaxaca. The peak cumulative slip of $\sim$30 mm (Fig. 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 $\sim$60 mm and an equivalent moment magnitude of 7.1.

6. Discussion

Our modeling indicates that the SSEs that occurred in early 2006 and early 2007 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]. All three of these SSEs occurred at depths below the seismogenic zone and had equivalent moment magnitudes of 7.0-7.3. The available data do not require any along-strike, updip, or downdip migration of the transient slip during either the 2006 or 2007 SSE. 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 energy that accumulates downdip from the seismogenic zone.

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]. Our own modeling and that of *Larson et al.* [2007] both indicate that the 2006 SSE beneath Guerrero extended upward into the seismogenic zone. Modeling by other authors of the SSE in 2001-2002, which was recorded by fewer GPS stations, does not clearly establish whether slip intruded upward into the seismogenic zone during that event [*Kostoglodov et al.*, 2003; *Iglesias et al.*, 2004; *Larson et al.*, 2004; *Yoshioka et al.*, 2004]. However, the transient offsets measured at the coastal sites in Guerrero in both 2002 and 2006 were roughly a factor-of-five greater than the offsets measured at sites in the volcanic belt (~50 mm versus ~10 mm) [*Franco et al.*, 2005; *Larson et al.*, 2007] and thus define a similar pattern of deformation that may suggest that transient slip in 2002 also extended to seismogenic depths.

The available evidence indicates that the SSEs beneath Guerrero and Oaxaca in 2006 and 2007 were distinct in space and time. The SSE source regions beneath Guerrero and Oaxaca were separated by at least ~100 km (Figs. 3c, 4, and 5) and gave rise to different patterns of surface deformation consistent with shallower and larger magnitude transient slip beneath Guerrero than beneath Oaxaca. 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 (Fig. 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 2007 SSE may have migrated slowly to the east in the latter half of 2007. This remains a topic of future study.

Our results have possibly useful implications for understanding past and future SSEs in southern Mexico. Based on an analysis of continuous and campaign GPS data that recorded the M_w=7.6 SSE that began in Guerrero in late 2001, *Franco et al.* [2005] propose that slip propagated to the east by ~2 km per day from a source region beneath Guerrero and triggered transient slip beneath western and central Oaxaca by March of 2002. However, since no GPS stations were operating within a 200-km gap (~100-98^{o}W) between Guerrero and Oaxaca at this time, the data do not unequivocally demonstrate that slip migrated across this gap.

Our modeling of the three 2006 and 2007 SSEs in Oaxaca and Guerrero shows no obvious spatial connection between these three SSEs even though they all occurred within a 16-month-long period. Similarly, the SSEs that were recorded in 2001 and 2002 in Guerrero and Oaxaca may have been distinct and unrelated despite their close temporal correspondence. Given that SSEs play a still poorly understood role in seismogenesis along the Mexican subduction zone, it is important to determine whether transient slip that originates in one source region can propagate hundreds of kilometers along strike and possibly increase the deep elastic loading that may trigger shallow megathrust earthquakes. An ongoing 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 Fig. 3c) and continuous broadband seismic stations we are operating at most of these sites, will significantly enhance determinations of the source region parameters of future SSEs in southern Mexico, and will help determine whether and how SSEs migrate along-strike and whether they are preceded by and possibly triggered by small earthquakes or are accompanied by non-volcanic tremor.

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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].

Figure 2. North component of GPS coordinate time series for 15 stations used in the analysis. The motion of the North American plate estimated using GPS stations from the plate interior is removed from each time series. Gray symbols show 24-hr station location estimates. 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.

Figure 3. 30-day transient offsets from hyperbolic tangent fits to time series in Fig. 2 (shown by blue arrows in the inset maps) 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 January 1, 2006 and ending October 27, 2006. (b) Best inverse models for slip during consecutive 30-day windows beginning February 24, 2007 and ending May 24, 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 zero millimeters. (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 Fig. 5.

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

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 Fig. 3c). Each line shows 30-day slip amount extracted from the best-fitting slip distributions shown in Fig. 3a-b. 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 January 1, 2006.

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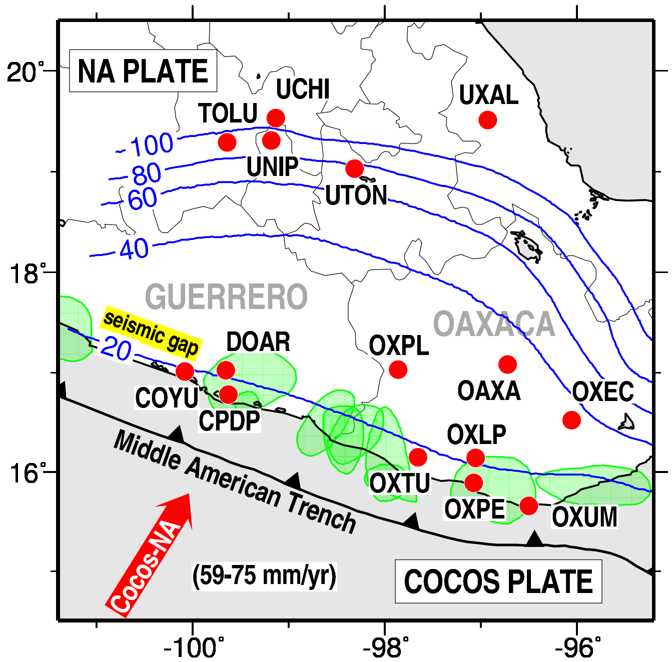

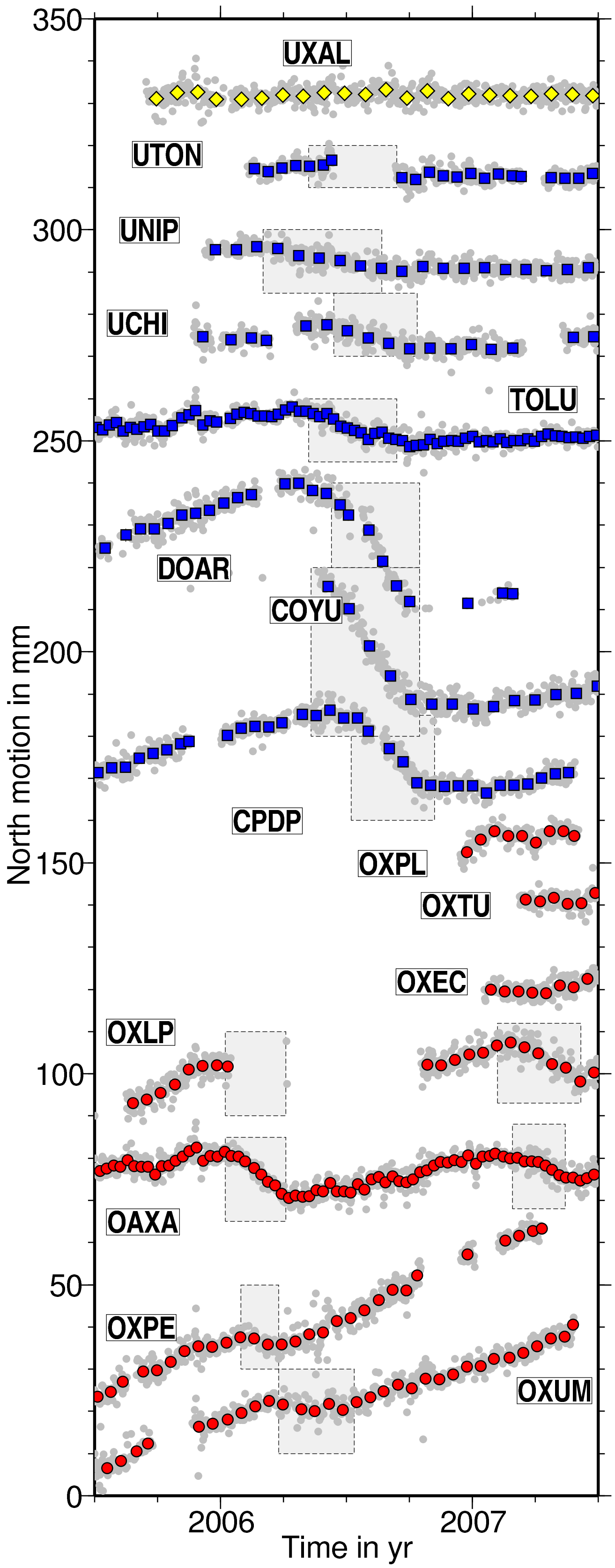

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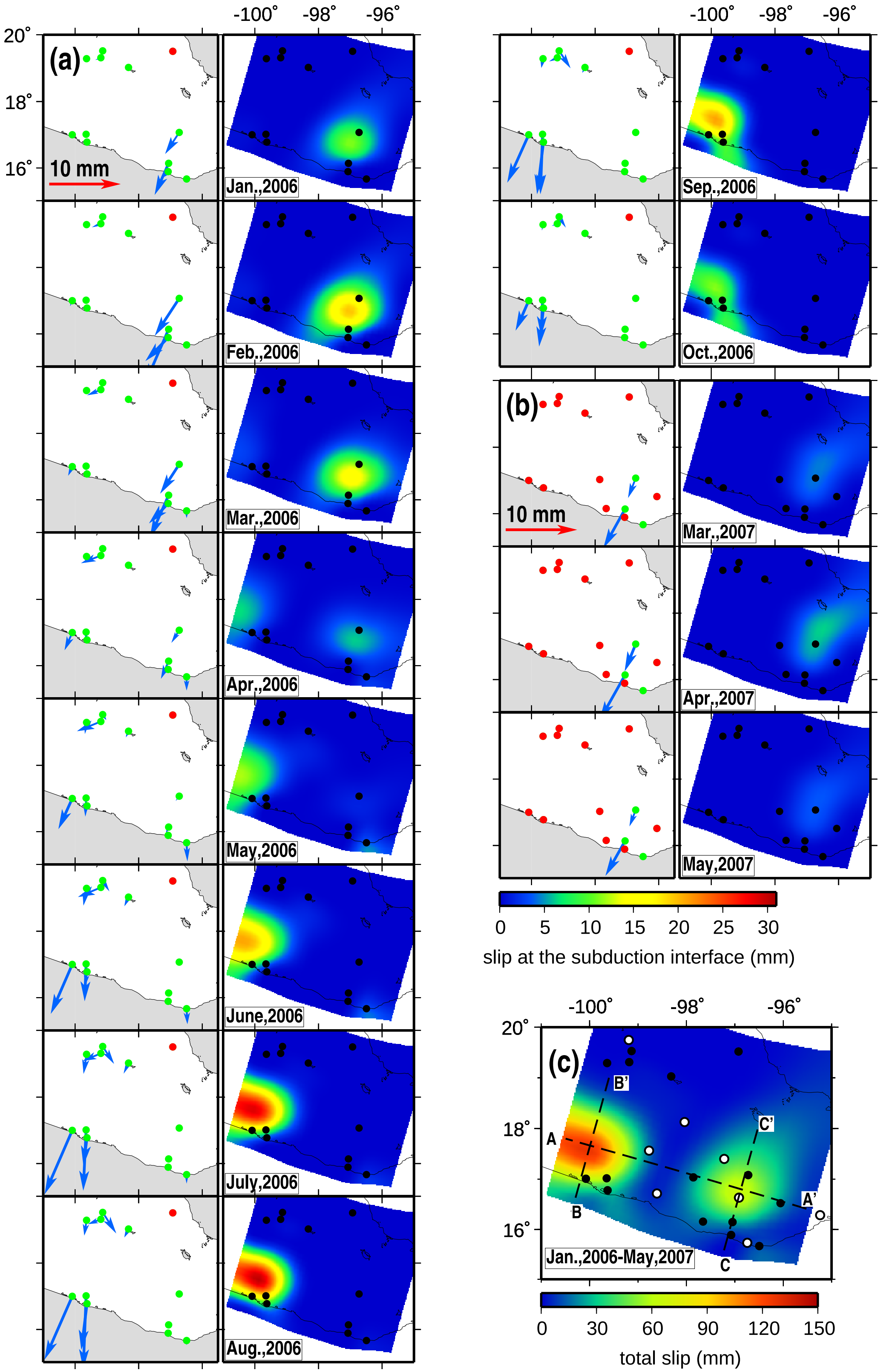

Fig. 3 - ***see end of text file for full caption***. 30-day transient offsets from hyperbolic tangent fits to time series in Fig. 2 (shown by blue arrows in the inset maps) and transient slip on the subduction interface that best fits the transient offsets (right).

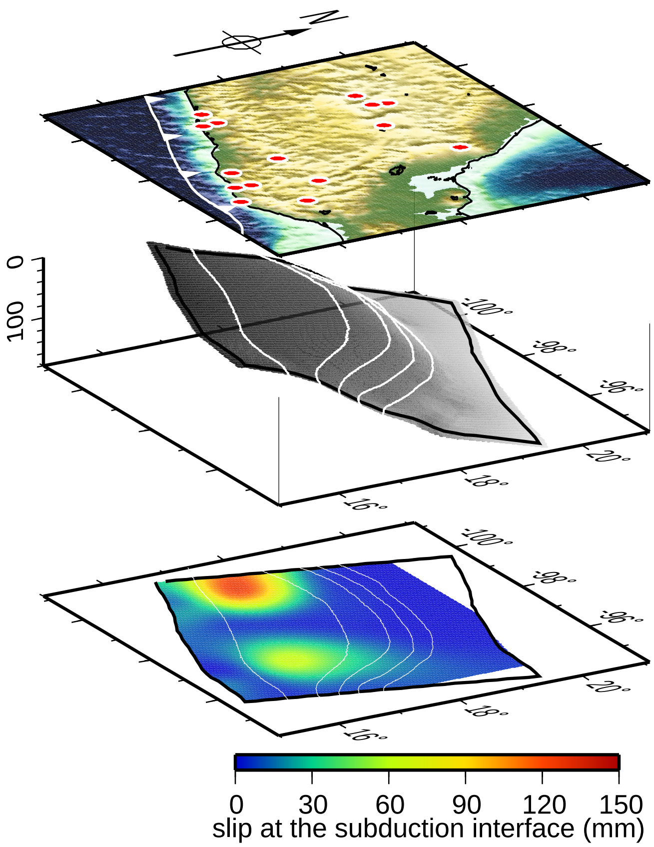

Fig. 4. Oblique views of GPS station locations (red circles) within the study area (upper), the subduction interface embedded in our finite element mesh and its 20 km depth contours (middle), and transient slip from Fig. 3c (lower).

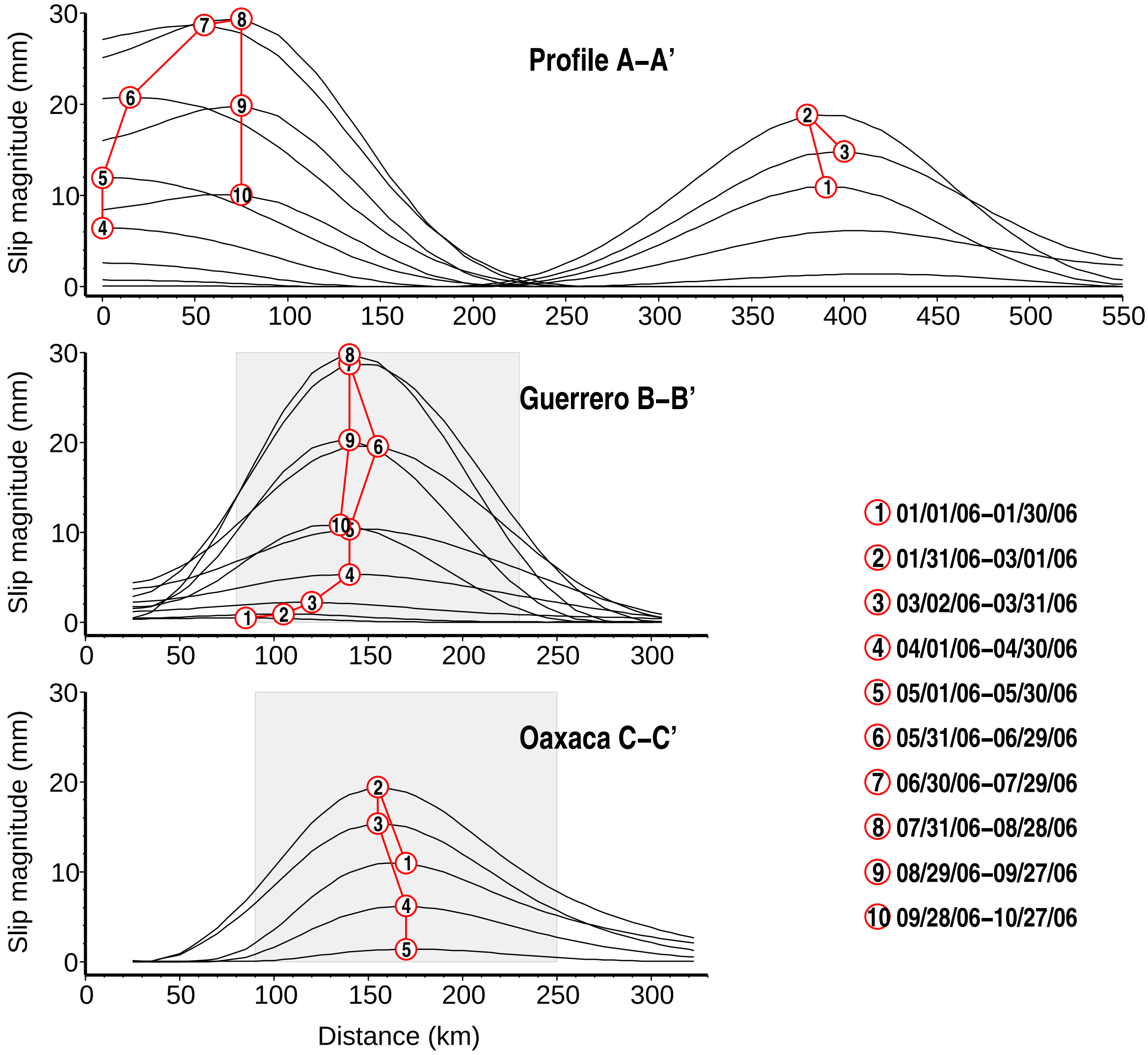

Fig. 5. Space-time evolution of transient slip along trench-parallel profile A-A' and trench-normal profiles B-B' in Guerrero and C-C' in Oaxaca (profile locations are shown in Fig. 3c). Each line shows 30-day slip amount extracted from the best-fitting slip distributions shown in Fig. 3a-b. Shaded rectangles 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 January 1, 2006.