Geophys. J. Int. (2007) **171,** 523–538 doi: 10.1111/j.1365-246X.2007.03542.x

Slow slip transients along the Oaxaca subduction segment from 1993 to 2007

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Accepted 2007 July 3. Received 2007 May 18; in original form 2006 December 8

SUMMARY

We use data from 12 continuous GPS stations in southern Mexico, including eight new stations, to better characterize transient slip episodes along the Mexican subduction zone. Continuous GPS recording in Oaxaca that began 14 years ago, constituting the longest continuous GPS record in southern Mexico, defines nine distinct episodes of transient slip from 1993 to 2007, including previously unreported transient slip episodes in early 1995 and 2006. All transient slip episodes recorded in Oaxaca City were also recorded at a GPS site ~400 km away in the state of Guerrero after measurements began there in early 1997, demonstrating that transient slip affects widespread areas of southern Mexico. Well-recorded transients in 2004 and 2006 appear to have originated along the Oaxaca trench segment, hundreds of kilometres from the potentially hazardous Guerrero seismic gap. During the 2004 slip transient, displacements of more than 20 mm were recorded at stations in the Oaxaca GPS array, a factor of 2–3 larger than at sites in Guerrero. Elastic half-space modelling of the 2004 displacements at sites throughout southern Mexico indicates that most slip was focused beneath Oaxaca in deeper areas of the subduction interface immediately downdip from previous megathrust rupture zones, but that slip also may have extended significantly updip into a seismic gap along the Oaxaca coast. The best-fitting model is also able to explain transient vertical offsets of up to 30 mm observed during this event. Shortly before the onset of transient slip in 2004, a pair of moderate (M_w 5.1, 5.5) earthquakes ruptured the downdip end of the seismogenic zone immediately east of the Oaxaca seismic gap, suggesting a possible relationship between the two. In 2006, transient slip began 1–3 months earlier in Oaxaca than in other areas, offering the clearest evidence to date for the existence of one or more source regions for transient slip outside the Guerrero seismic gap, where large amplitude transient slip originated in 2002. The still-limited data indicate that transient slip that originates elsewhere in Mexico may trigger aseismic slip in Guerrero, and further indicate that transient slip beneath Oaxaca is limited to areas of the subduction interface that surround the rupture zones of previous large shallow-thrust earthquakes.

Key words: subduction, aseismic transient, middle America trench.

1 INTRODUCTION

Most of the world's seismicity, including the largest earthquakes, is associated with interplate slip along convergent plate boundaries (e.g. Isacks *et al.* 1968; Kanamori 1977). Continuous motion of the converging plates produces tectonic loading of the locked segment of the plate interface, eventually leading to earthquake rupture. Downdip from the seismogenic zone, temperature-controlled rheology and friction allow smoother slip without producing earthquakes (e.g. Hyndman & Wang 1993). Such slip may be episodic and could trigger an earthquake in the updip seismogenic zone (e.g. Thatcher 1982; Linde & Silver 1989). Recent data from continuous Global Positioning System (GPS) sites indicate that transient aseismic slip occurs over large areas of the deeper subduction interface (e.g. Dragert *et al.* 2001; Ozawa *et al.* 2002; Szeliga *et al.* 2004) and may extend updip into the seismogenic zone (Ozawa *et al.* 2004, e.g. Yoshioka *et al.* 2004). If transient slip occurs preferentially near seismic gaps, as appears to be the case in the Tokai segment of Japan (Ozawa *et al.* 2002), it could influence the timing and location of future subduction thrust earthquakes (Kodaira *et al.* 2004).

The Mexican segment of the Middle America subduction zone (Fig. 1) has long been a key target for studies of seismogenesis along a subduction interface due to its relatively rapid convergence rates

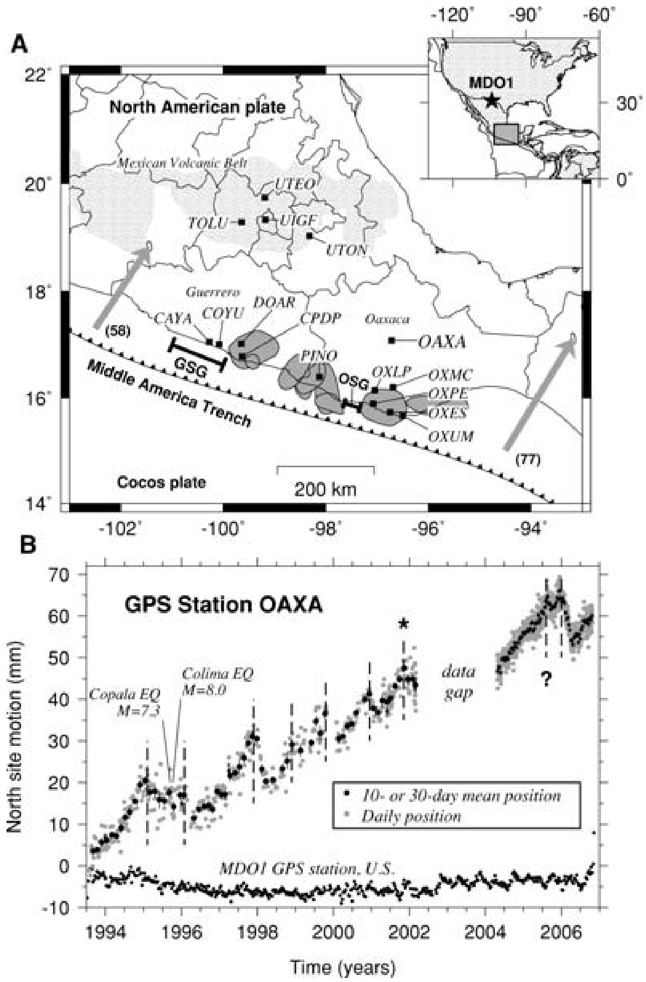

Figure 1. (a) Map of study area. Squares indicate GPS stations employed in this analysis. Shaded regions along Pacific coastline are approximate rupture zones of large subduction thrust earthquakes over the past 50 yr as estimated from locations of rupture aftershocks. GSG and OSG specify the Guerrero Seismic Gap and Oaxaca Seismic gap, respectively. Arrows and parenthetical numerals show Cocos-North America plate convergence velocities in mm yr^{-1} (DeMets 2001). (b) North component of the GPS coordinate time-series for INEGI station OAXA, 1993.5–2006.8. Shaded and solid circles show 24-hr and monthly location estimates, respectively. Vertical dashed lines indicate onset times of transient motion. Line marked by asterisk indicates onset of 2002 transient reported for the Guerrero seismic gap (Kostoglodov *et al.* 2003). Monthly locations for site MD01 in Texas, in the stable plate interior, are shown to illustrate the magnitude of likely random and other noise that also affects the OAXA time-series.

(50–70 mm yr^{-1}), small trench-to-coast distances, shallow subduction angles and a short earthquake cycle (30–100 yr) (Anderson 1989; Kostoglodov & Ponce 1994). In particular, the Oaxaca segment from 98.5°W to 95.5°W is distinguished by trench-to-coast distances of less than 50 km, such that the seismogenic and transitional zones of the subduction interface extend up to 250 km inland from the coast and hence can be studied in detail with GPS. Developing a better understanding of the earthquake cycle along the Mexican segment of the Middle America trench is clearly important because of the threat posed by subduction thrust earthquakes to Mexico City, where more than 10 000 casualties and billions of dollars of damage occurred during the devastating 1985 Michoacan earthquake (e.g. Beck & Hall 1986).

A comparison of the cumulative seismic moment that has been released by shallow subduction thrust earthquakes along the Mexican subduction zone over the past century to that predicted by a model in which all Cocos-North American plate convergence is eventually released by such earthquakes shows that there are significant variations in the degree of seismic coupling along the Middle America trench (Pacheco *et al.* 1993). The segment with the largest seismic slip deficit, located off the coast of the Mexican state of Guerrero (GSG in Fig. 1), has accumulated enough unrelieved elastic strain since the most recent earthquake in 1911 to unleash a shallow thrust earthquake of $M_w = 8.1$–8.4 if all of that slip were recovered in a single future earthquake (Suárez *et al.* 1990).

GPS measurements in southern Mexico, mostly at sites in the state of Guerrero, have recorded aseismic slip transients in late 1995/early 1996, 1998 and 2002 (Lowry *et al.* 2001; Kostoglodov *et al.* 2003; Larson *et al.* 2004) that appear to be focused near the Guerrero seismic gap. Detailed studies of deformation before and during these transient slip events show that they consist of several-week-long to several-month-long periods during which GPS site directions reverse from northeast-directed trench-normal elastic shortening characteristic of interseismic strain buildup to trenchward motion, indicative of the release of interseismic strain (e.g. Kostoglodov *et al.* 2003; Yoshioka *et al.* 2004). At station CAYA within the Guerrero seismic gap, the improvement in fit of a model that allows for transient slip events relative to the fit of a simple linear-motion model is significant at very high confidence levels. Modelling of static site displacements as large as 30 mm over a several month period in 1998 and 50 mm during the 2002 transient indicates that the seismic energy released by the 1998 and 2002 transients has equivalent moment magnitudes of $Mw = 6.5$ and 7.4 (Lowry *et al.* 2001; Kostoglodov *et al.* 2003). Modelling of the surface deformation measured during the 2002 transient also suggests that some slip may have propagated far enough up the subduction interface to relieve strain along its seismogenic portion (Yoshioka *et al.* 2004), thereby raising the question of whether transient slip plays a role in modulating the earthquake cycle in this region.

To date, most continuous GPS measurements in southern Mexico region have been focused in the state of Guerrero, thereby leaving large voids in our understanding of the source regions of these transients, the extent to which they propagate in space and time along the subduction interface, and their physical causes. In this paper, we combine new continuous observations from a six-station GPS array in Oaxaca and a four-station array in the Mexican volcanic belt with data from four existing GPS sites in Guerrero (Fig. 1) to further examine and characterize episodic slow slip in southern Mexico. Following brief descriptions of the data and methods that are the basis for our analysis, we use a 13-yr-long continuous time-series from station OAXA in southern Mexico to establish the frequency and timing of episodic slow slip in southern Mexico since mid-1993 and further demonstrate a correspondence between transient displacements recorded at sites OAXA in Oaxaca and CAYA in Guerrero during 1997–2003. We next use the GPS coordinate time-series analysis and elastic half-space modelling to establish the existence, timing and magnitude of motion during a well-recorded transient slip episode in 2004. Finally, we present evidence and modelling of a slow slip episode that was first recorded in Oaxaca in early 2006 and then recorded 2–3 months later at sites in Guerrero and the Mexican volcanic belt.

2 THE MIDDLE AMERICA TRENCH SEISMOGENIC ZONE, 101–95°W AND AN APPARENT OAXACA SEISMIC GAP

As part of our study of the source zone of transient slip in southern Mexico, we recompiled the aftershock zones for large earthquakes over the past 50 yr that have ruptured the Mexican subduction zone from 101 to 95°W, the approximate limits of our study area (Fig. 1, Tajima & McNally 1983; Astiz & Kanamori 1984; Courboulex *et al.* 1997; Singh *et al.* 1997). The aftershock zones are confined largely to areas of the subduction interface located offshore or beneath coastal regions (Fig. 1), consistent with the suggestion by Suarez & Sanchez (1996) that the general absence of large ($M_w > 8$) earthquakes along the Cocos-North America subduction interface reflects a possible shallow (∼20 km) locking depth for much of the Middle America trench.

Our recompilation confirms the rupture areas that are depicted in numerous previous publications, with one exception, namely, an apparent ∼50-km-wide seismic gap from 97.7 to 97.3°W off the coast of Oaxaca (Fig. 1). The primary evidence for the existence of this apparent seismic gap comes from a Joint Hypocentral Determination of the aftershock sequences of the $M > 7$ 1965, 1968 and 1978 earthquakes (Tajima & McNally 1983) which revealed a ∼5000 km^2 area devoid of aftershocks between the 1968 and 1978 rupture zones. Our own examination of relocated hypocentres of moderate ($m_b \geq 5$), teleseismically and regionally recorded earthquakes (Pardo & Suarez 1995; Engdahl *et al.* 1998; Engdahl & Villasenor 2002) since 1964 also shows few earthquakes within this particular region. Hereafter, we refer to this feature as the Oaxaca seismic gap.

3 DATA AND METHODS

3.1 GPS observations and analysis techniques

The data used below come from GPS stations that have been installed at various times since 1993 and are operated by different groups, most with the objective of studying the tectonics and earthquake hazards of Mexico. Data from station OAXA in central Oaxaca (Fig. 1), which is operated by the Mexican federal agency INEGI, span the period from mid-1993 to early 2002 and from early 2004 to the present (2006.8). These constitute the longest continuous GPS time-series of any near-trench station in southern Mexico (negotiations are ongoing for access to data from the 2-yr gap between early 2002 and early 2004). Marquez-Azua & DeMets (2003) describe the processing and results for OAXA and other INEGI data from times before mid-2001, for which we have only 1 d of data per week. Daily data from this station have been publicly available since mid-2004.

We also use new data from five GPS stations that we installed in Oaxaca in 2001 and 2002 (OXES, OXLP, OXMC, OXPE and OXUM). Two of these stations (OXLP and OXMC) are in remote areas and have gaps in their time-series due to equipment and power failures. New data from stations UIGF, UTEO, UTON and INEGI site TOLU extend the station coverage to locations well inboard from the trench. Finally, we also use data from stations CAYA, COYU, CPDP and DOAR in Guerrero, all of which are public domain sites within a broader GPS network operated by UNAM (e.g. Kostoglodov *et al.* 2003).

We analysed all GPS code-phase measurements using GIPSY analysis software, precise satellite orbits and clocks from the Jet Propulsion Laboratory (JPL), and a standard point-positioning strategy (Zumberge *et al.* 1997). Daily station coordinates were first estimated in a no-fiducial reference frame (Heflin *et al.* 1992) and then transformed to ITRF2000 (Altamimi *et al.* 2002) using daily seven-parameter Helmert transformations from JPL. The raw coordinate time-series exhibit daily scatter of 3–4, 4–6 and 9–11 mm for the north, east and vertical components, respectively, and longer-period noise with typical amplitudes of 5–10 mm in all components.

An analysis of the daily and longer-period noise at several hundred GPS stations from the North American plate shows that the noise is significantly correlated over intersite distances as far as 2000 km (Marquez-Azua & DeMets 2003). Following procedures described by Marquez-Azua & DeMets (2003), we estimated and removed spatially correlated noise from the coordinate time-series of Mexican GPS stations using coordinate time-series for ∼700 additional stations in North America, Central America and the Caribbean. The corrected coordinate time-series have daily scatter in their north and east components of 1.5–2 and 2.5–3 mm, respectively, and long-period noise amplitudes of 3 mm or less. Only sites external to southern Mexico and the Mexican Volcanic Belt are used to estimate and remove the common-mode noise, thereby preserving any tectonic transients that might be present in the coordinate time-series for sites in southern Mexico. The common-mode-corrected time-series for site MDO1 in the plate interior (Figs 1 and 2) illustrates that annual and other long-period departures from linear site motion have amplitudes of 2 mm or less. This presumably non-tectonic noise establishes an approximate upper bound on the smallest transient offset that we can hope to detect.

All station motions are described relative to the North American plate interior, as defined by the motions of ∼350 continuous stations that are located north of the Mexican Volcanic Belt and outside areas of Canada and the northeastern United States that are affected by postglacial rebound (Calais *et al*. 2006). The uncertainties in the angular velocity vector that we use to transform the site velocities from ITRF00 to a North American plate reference frame are tenths of a millimetre per year at locations in Mexico and do not represent a limiting factor in the analysis.

3.2 Estimation of transient slip characteristics from GPS coordinate time-series

Following Lowry *et al*. (2001) and Larson *et al.* (2004), we estimate cumulative station displacements during transient slip events by fitting the GPS coordinate time-series with a function of the form

$$x(t) = x_0 + Vt + \Sigma_{i=1}^{n}\{U_i/2[\tanh(t - T_{0i}/\tau_i) - 1]\} \quad (1)$$

in which $x(t)$ are GPS site coordinates at time t, x_0 are coordinates at a reference time, V is the steady-state velocity, U_i is anomalous displacement during the ith of n transient events, T_{0i} is the median time of the ith event, and τ scales the period over which the event occurred. Once T_0 and τ are specified, the steady-state velocity V and transient displacements U_i are estimated via a standard, weighted least squares minimization procedure. The hyperbolic tangent fit is used for mathematical convenience, but is unlikely to have any physical significance for slow slip processes.

Following the work of Holtkamp *et al*. (2006), we automated the procedure for identifying significant transients by undertaking a grid search over T_0 and τ. For each pair of T_0 and τ, we apply the hyperbolic tangent fit over a 12 month scrolling window incremented at 0.01 yr, and use an F-ratio test to determine whether a hyperbolic tangent curve fits the coordinate time-series significantly better than does a linear fit at 99 per cent confidence within the window. We mark all events that exceed a threshold value for transient

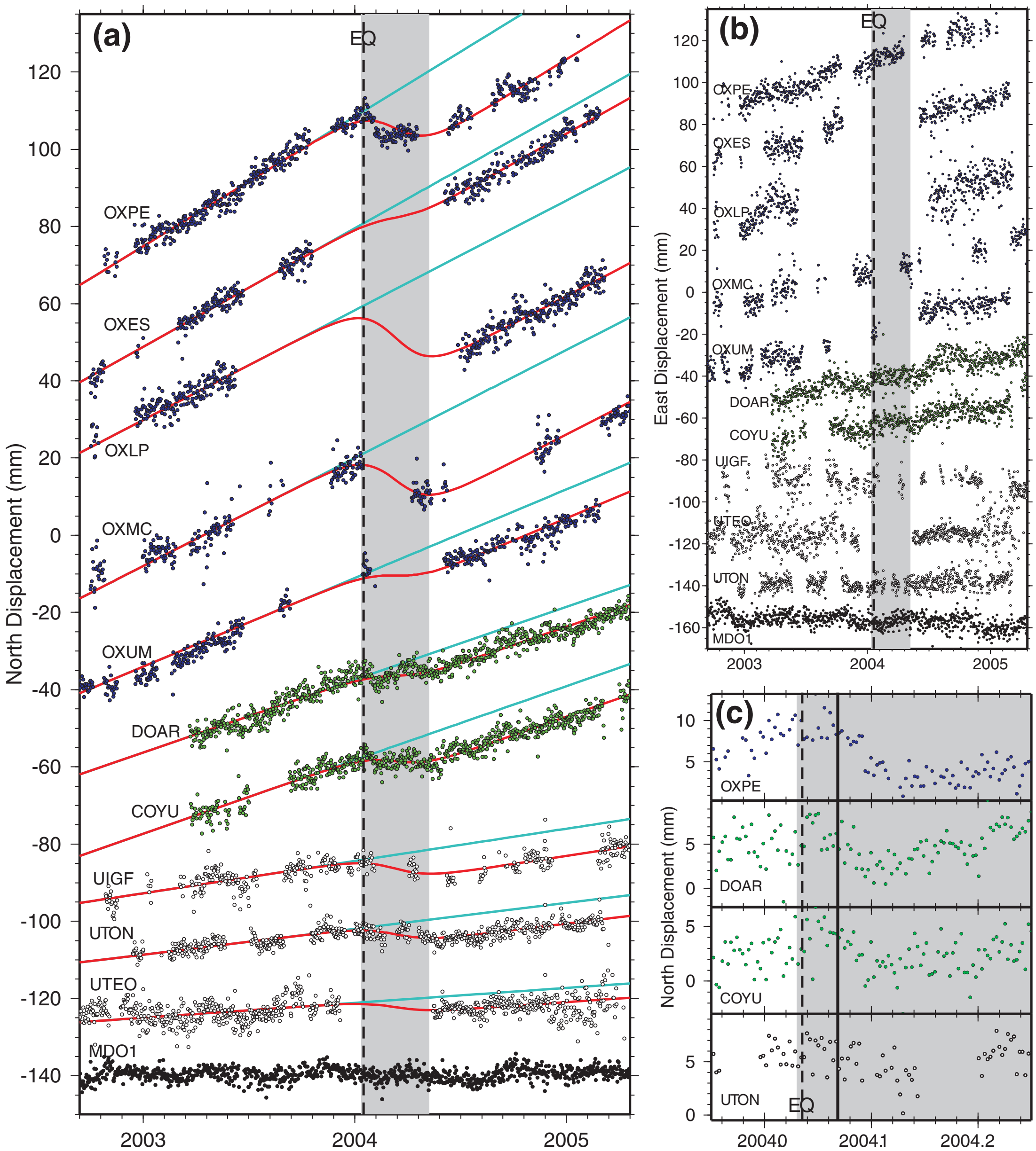

Figure 2. Time in years versus displacement for continuous GPS stations in southern Mexico spanning the 2004 transient slip episode. Steady motion of North American plate is removed. Solid curves show hyperbolic tangent fits. Midpoint and width of shaded band represent best estimates of T_0 and τ from inversion procedure described in Section 3. Transient magnitude at each site is determined from the offset of the red and blue lines. Site MDO1 (Fig. 1) is included to demonstrate that the transients are not merely common-mode non-tectonic noise. (a) North component. (b) East component. The relative absence of transient motion in the east component indicates that transient motion was dominantly southward. (c) North components of site motions at OXPE, DOAR and COYU illustrating that the departure from background scatter (solid line) occurs ~6 d after a pair of moderate earthquakes (dashed line) near OXLP (Fig. 3).

displacement, with the threshold value based on the average amplitude of background noise (~3 mm) that is present in the time-series of stable sites located in the plate interior.

Significant gaps in measurements at several sites during the 2004 transient (Fig. 2) preclude a reliable assessment of where slip originated and how it propagated during that transient. We thus jointly inverted the data from all the sites to estimate a common transient midpoint T_0 and duration time τ, and individual transient displacement amplitudes at each site. As can be seen from Fig. 2a, the transient midpoints and duration times at different sites are approximately the same in 2004. Small departures at individual stations from constant values for these two parameters are unlikely to change significantly our estimates of the amplitude of transient motion at those sites, which are relatively insensitive to small errors in our estimates of T_0 and τ. Estimating only these two parameters instead of separate values of T_0 and τ at each at the 10 stations that were recording in 2004 improves our estimates of the remaining parameters, including the amplitude of transient displacement at each site that we use for our elastic half-space modelling. Uncertainties in the displacement amplitudes for the north, east and down components are estimated by using an F-ratio test to determine values for the displacement amplitudes that give rise to least-squares misfits χ^2 to the GPS time-series that exceed χ^2 for the best-fitting model at the 1σ level.

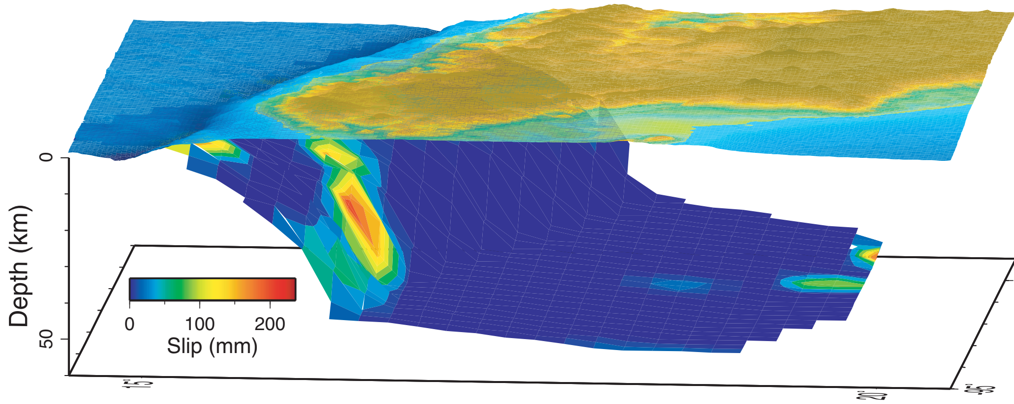

Figure 3. 3-D rendition of the subduction interface geometry used in modelling the slip distribution. The surface is constructed from the grid nodes where slip is evaluated. Along-strike shape of fault is from the curvature of the trench, and dip of the fault is approximated from that of Kostoglodov *et al.* (1996). Slip magnitudes shown on the subduction interface are the best-fitting solution for the 2004 slip event described later in the paper. Stars are locations of moderate 2004 January earthquakes that immediately preceded transient motions.

3.3 Estimation of the distribution of slow slip on the subduction interface

We use finite element modelling and standard inversion techniques to estimate the spatial distribution of slip along the subduction interface during the slow slip events, assuming that surface deformation associated with the slow slip represents elastic deformation that is induced by slip along the subduction interface. The study area is approximated using a 3-D finite element mesh that uses spherical coordinates, a spherical earth geometry and incorporates the relatively flat geometry of the Middle America subduction zone (Fig. 3) described by Kostoglodov *et al.* (1996). The upper surface of the mesh employs continental topography and seafloor bathymetry, and the lower and lateral boundaries of the mesh are extended far enough from the study area to avoid any modelling artefacts associated with the mesh boundaries. The thicknesses and elastic properties for the oceanic crust and upper-, middle- and lower layers of the continental crust are derived from the seismically based CRUST2 model (http://mahi.ucsd.edu/Gabi/rem.dir/crust/crust2.html; Bassin *et al*. 2000).

We estimate the magnitude of slip at each of the m nodes that define the subduction interface by solving the linear system $\mathbf{G}\ \mathbf{m} = \mathbf{d}$, where $\mathbf{d}$ is a $3n$-element vector that contains the 3-D transient offsets recorded at n GPS sites, $\mathbf{m}$ is a vector that contains the best estimate of the slip at each node, and $\mathbf{G}$ is a $3n \times m$ matrix that specifies the 3-D elastic response at each GPS site to assumed unit slip at each of the mesh nodes.

We calculate values for $\mathbf{G}$ using the commercial finite element package *ABAQUS*. Separate data kernels for unit downdip ($\mathbf{G_{ds}}$) and strike-slip ($\mathbf{G_{ss}}$) offsets were constructed initially to enable a systematic search for the slip direction that best fits the observed transient offsets. For a given rake angle ϕ that is defined relative to the known strike of the trench, the total surface response $\mathbf{G}$ is calculated as a sum of the two orthogonal kernels $\mathbf{G} = \mathbf{G_{ds}} \sin\phi + \mathbf{G_{ss}} \cos\phi$.

We define the best slip distribution by minimizing the least-squares misfit χ^2 in the presence of data uncertainties and imposing smoothing constraints and a constraint that enforces uniform-sense slip (downward motion of the oceanic slab) using the non-negative least squares method (Lawson & Hanson 1974). We use the L-curve criterion (Hansen 1992) to identify the smoothing coefficient that optimizes the usual trade-off between the high misfits and oversimplified slip distributions that are associated with overly smoothed solutions and the low misfits and unjustifiably complex slip distributions that are associated with insufficiently smoothed solutions. The fitting equation treats the smoothing constraints as pseudo-data that augment the linear system, as follows:

$$\left|\begin{matrix} \boldsymbol{WG} \\ \alpha\mathbf{F} \end{matrix}\right| \mathbf{m} = \left|\begin{matrix} \mathbf{wd} \\ \mathbf{0} \end{matrix}\right|, \tag{2}$$

where α and $\mathbf{F}$ are the smoothing coefficient and smoothing matrix, respectively, and $\mathbf{W}$ is a squared diagonal matrix containing the reciprocal of the data uncertainties.

4 LONG-TERM OBSERVATIONS OF TRANSIENT SLIP IN OAXACA: 1993–2006

The only continuous GPS stations operating in Mexico before January of 1997, when station CAYA was installed along the Pacific coast of Guerrero (Lowry *et al.* 2001), consisted of 15 GPS sites operated by INEGI (Marquez-Azua & DeMets 2003). Of these, only OAXA was located south of volcanic belt and was well positioned to record transient slip associated with the subduction interface. Table 1 summarizes the results of a systematic examination of the 1993–2006 coordinate GPS time-series at OAXA and other stations in southern Mexico using the automated search algorithm described in Section 3. Evidence for highly significant transient slip displacements at OAXA exists for 1995, 1996, 1998, 1999, 2000, 2001, 2002 and 2006 (DeMets *et al.* 2004). Data from other sites in Oaxaca during the 2002–2004 data gap at OAXA clearly show offsets indicating that transient slip also occurred in 2004 (Section 5). In addition, several millimetres of transient slip displacement may also have occurred in early 1997 and the latter half of 2005, although we are less confident about these due to their small amplitudes. No significant transient slip displacement (>3 mm amplitude) occurred in 1994, 1997, 2003 and 2005. Transient slip displacements exceeding 3 mm thus failed to occur during 4 of the 13 yr that continuous GPS observations have been made in Oaxaca. Slip displacements during eight of the nine transient episodes began in December or January. Slip in 1996 appears to have initiated in March. In all cases, the direction of transient slip displacement was dominantly towards the Middle America trench (upper maps in Fig. 4), consistent with a protracted release of elastic strain related to subduction.

Table 1. Slip transient characteristics: 1993–2006.

Event	Station	T_0 (yr)	τ (yr)	U_{North} (mm)		U_{East} (mm)		U_{Up} (mm)		V_{North} (mm yr^{-1})	V_{East} (mm yr^{-1})	V_{Up} (mm yr^{-1})	F_{North} $(1-p)$	F_{East} $(1-p)$	F_{Up} $(1-p)$
1995	OAXA	1995.3	0.21	−5.4	−1.1/1.1	8	−2.3/2.2	−6	−2.8/2.7	10.5	−13.6	7.1	99.083	93.68	33.7
1996	OAXA	1996.25	0.01	−3.2	−0.9/0.9	−0.8	−0.4/0.4	−4.1	−2.1/2.1	5.2	−6.1	9.5	99.804	2.9	51.3
1998	OAXA	1998.11	0.12	−10.4	−0.8/0.8	−7.4	−1.5/1.7	−1.9	−0.9/0.9	18	21.3	8.7	100	99.911	2.1
1998	CAYA	1998.17	0.2	−14.9	−0.4/0.4	3.1	−1.2/1.2	10.5	−2.0/1.9	19.2	9.9	−18.8	100	77.9	99.862
1999	CAYA	1999.18	0.11	−2.3	−0.5/0.5	−0.9	−0.5/0.5	1.9	−1.0/1.0	18.4	9.2	−19.9	99.849	11.9	18.4
1999	OAXA	1999.2	0.21	−3.1	−1.3/1.3	−6.4	−1.8/1.8	13.5	−4.9/4.3	16.4	16.9	−29.6	96.66	92.89	78.2
2000	OAXA	2000.07	0.04	−6.3	−0.9/0.9	−1	−0.5/0.5	−0.3	−0.2/0.2	16.2	5.7	−12.7	100	3.6	0.1
2000	CAYA	2000.16	0.15	−3.4	−0.5/0.4	0.6	−0.3/0.3	1.2	−0.6/0.6	22.5	10.3	−15.9	100	5.1	3.7
2001	OAXA	2001	0.15	−5.4	−0.5/0.5	−8.1	−1.6/1.4	0.9	−0.5/0.5	16.1	19.8	2.7	100	99.871	0.5
2001	CAYA	2001.01	0.21	−4.6	−0.2/0.4	0.3	−0.2/0.2	13.8	−2.1/2.1	24.2	11.4	−27.4	100	0.1	99.985
2002	CAYA	2002.1	0.19	−32.9	−0.3/0.3	−21.4	−1.3/1.1	30	−2.7/2.4	30	33.2	−8.1	100	100	100
2002	OAXA[a]	2002.1?													
2004	COYU	2004.19	0.16	−3.2	−0.3/0.4	0.3	−0.2/0.2	6.6	−1.3/1.3	18.5	7.6	−16.3	100	0	99.998
2004	DOAR	2004.19	0.16	−1.8	−0.3/0.3	1.2	−0.5/0.6	−3	−1.4/1.5	18.2	9.3	6.9	100	11.5	65.5
2004	OXES	2004.19	0.16	−2.4	−0.2/0.3	−3.3	−0.7/0.7	7.8	−1.6/1.5	30.1	17	−12	100	99.901	99.817
2004	OXLP	2004.19	0.16	−12.3	−0.4/0.4	−10.7	−1.5/1.4	24.5	−2.2/2.7	28.6	18.7	−27.2	100	99.903	100
2004	OXMC	2004.19	0.16	−10.3	−0.6/0.5	−0.2	−0.1/0.1	14.3	−2.1/2.1	27.2	11.4	−11.7	100	0.3	100
2004	OXPE[b]	2004.19	0.16	−8	−0.2/0.3	1.3	−0.5/0.6	4.6	−1.1/1.1	31.8	16.4	−2.1	100	97.73	98.71
2004	OXUM	2004.19	0.16	−3	−0.3/0.3	4.7	−0.6/0.6	1.5	−0.7/0.7	22.3	9.9	−4	100	100	10
2004	UIGF	2004.19	0.16	−2.8	−0.4/0.4	3.1	−0.7/0.7	13.3	−2.1/1.7	7.7	−5.7	−25.7	100	99.869	100
2004	UTEO	2004.19	0.16	−1.5	−0.4/0.3	−2.6	−0.7/0.5	14.9	−1.6/2.4	3.7	5	−25.2	99.999	98.36	100
2004	UTON	2004.19	0.16	−2.3	−0.2/0.3	0.7	−0.3/0.3	4.5	−1.3/1.4	6.4	−1	−10	100	58.3	99.919
2006	OAXA	2006.14	0.12	−7.9	−0.3/0.2	−0.5	−0.2/0.2	1.9	−0.9/0.9	11.7	−0.8	−7.6	100	19.8	56.2
2006	OXPE	2006.16	0.15	−6.7	−0.1/0.1	−2.5	−0.8/0.8	10.4	−1.8/1.7	30.3	21.5	−14	100	98.08	100
2006	OXUM	2006.3	0.08	−5.9	−0.3/0.3	1.7	−0.7/0.7	4	−1.6/1.6	27.6	8.2	−7.3	100	93.47	92.38
2006	OXES	2006.33	0.21	−8	−0.9/0.9	−0.4	−0.2/0.2	11.1	−1.0/1.0	35.7	10.1	−0.6	100	1.2	99.846
2006	UTEO	2006.34	0.05	−1.5	−0.3/0.3	2.4	−1.0/0.5	−0.9	−0.5/0.5	3	−4.5	−3.4	99.853	97.41	0
2006	UIGF	2006.4	0.07	−3.5	−0.3/0.3	0.7	−0.3/0.3	−4	−1.4/1.4	6.1	2	11.6	100	45.9	99.436
2006	TOLU	2006.43	0.1	−4.4	−0.2/0.3	−0.8	−0.4/0.4	−8.2	−1.1/1.1	6.5	4.1	27.8	100	58.1	100
2006	COYU	2006.47	0.17	−19.8	−0.6/0.4	0	−0.0/0.0	8.4	−2.5/2.5	15.2	16.6	13.8	100	0.1	94.58
2006	CPDP	2006.47	0.12	−3.4	−0.6/0.6	3.4	−1.1/1.1	−4	−2.0/2.0	13.2	11.1	21.2	100	99.996	77.8
2006	DOAR	2006.49	0.17	−11.1	−0.8/0.7	9.3	−0.4/0.4	−8.2	−3.5/2.7	19.2	−0.1	18.1	100	100	89.4

Definitions of T_0 and τ are given in Section 3. North, east and vertical components of the estimated site motion due to transient slip are given by U_{North}, U_{East} and U_{Up}. Note that offsets given by U are equal to half the magnitude of the total offset per component, as defined by (1). F_{North}, F_{East} and F_{Up} summarize results of F-ratio tests for the formal significance of the improvement in fit for eq. (1) versus a straight-line fit. p is the probability that the observed improvement in the least-squares fit is solely attributable to random chance. $1-p$ is thus the confidence level associated with the improvement in fit. Values of 1 - p greater than 0.99999 are rounded to 1.0.

[a]Transient at OAXA in 2002 has only partial data coverage (Fig. 1b)—estimates of its timing, significance and cumulative displacement are not yet available.

[b]Analysis of this time-series alone yields $T_0 = 2004.07$, as described in Section 5.

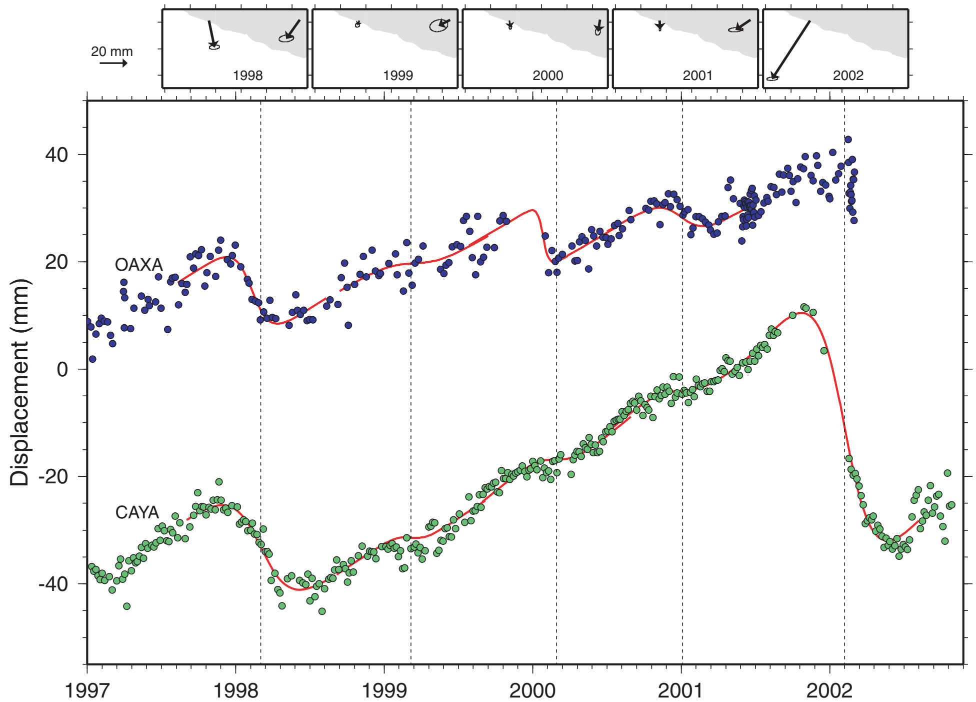

Figure 4. Comparison of GPS displacements in Oaxaca (OAXA) and Guerrero (CAYA) from 1997 to 2003. Lower panel shows continuous GPS time-series for the north component and best-fitting hyperbolic tangent curves for transient episodes. T_0, the transient midpoint, is marked for CAYA by the vertical dashed lines. OAXA time-series employs daily location estimates and CAYA time-series employs a five-sample running mean. Upper panels display transient displacements for each station based on best hyperbolic tangent fits to north and earth time-series for each transient episode. Site motions are specified relative to the North American plate.

The OAXA time-series thus contains the first evidence for a formerly unknown transient slip episode in early 1995 and confirms the existence of transient slip in late 1995 or early 1996 that is postulated by Larson *et al.* (2004) from campaign GPS observations from Guerrero. An analysis of these transient displacements in the context of the motions of the other INEGI sites during these times is reserved for a future paper.

Fig. 4 summarizes the motions of sites CAYA in Guerrero and OAXA in Oaxaca for the period from 1997 to 2003, during which relatively complete data are available for both sites. Despite the 380 km distance between these two stations, their time-series exhibit a clear correspondence between the transient movements that occurred annually from 1998 to 2002. Apparent transient slip recorded at CAYA in early 1997 also appears to have occurred at OAXA at the same time (Fig. 1b), but the ∼2 mm offset at OAXA falls below the cut-off threshold that we adopted for our automated search algorithm. Together, these time-series illustrate that slow slip events are common in southern Mexico and a major feature of the signal in the earthquake cycle. This reinforces conclusions reached previously by Kostoglodov *et al.* (2003), Larson *et al.* (2004) and Franco *et al.* (2005).

A final notable feature of the motions of sites CAYA and OAXA is the tendency for their transient motions to point towards a location somewhere east of the Guerrero seismic gap, as is shown in the upper panels of Fig. 4. Motions during the 1998, 1999, 2000 and 2001 transient slip episodes all show this pattern. Only the well-described 2002 transient slip episode was uniformly to the south–southwest (Kostoglodov *et al.* 2003; Yoshioka *et al.* 2004) and almost certainly originated immediately downdip from the Guerrero seismic gap. The patterns of deformation prior to 2002, though based on the motions of only two stations, raise the question of whether transient slip in 1998–2001 originated somewhere east of the Guerrero seismic gap. We next explore this hypothesis in more detail using data for the better-recorded transient slip episodes that occurred in 2004 and 2006.

5 TRANSIENT SLIP IN 2004: OBSERVATIONS, MODELLING AND RESOLUTION

5.1 Deformation pattern and timing

Between January and March of 2004, the coordinate time-series for 10 GPS stations that were operating in southern Mexico and the Mexican Volcanic Belt show clear reversals in their direction of motion, consisting primarily of southward motion towards the Middle America subduction zone (Figs 2a and 5) and negligible uplift along the Oaxacan coast increasing to as much as 49 ± 5 mm in its mountainous interior (Fig. 6). Fitting the time-series of the 10 stations that recorded the 2004 transient using (1) and procedures described in Section 3 yields slip displacements of 5–25 mm (Figs 2 and 5), with maximum slip displacements that are factors of 3–5 larger at sites in Oaxaca than in Guerrero and the distant Mexican Volcanic Belt (Table 1). This is unlike the patterns of transient deformation recorded in 1998 and 2002 (Fig. 4, Lowry *et al.* 2001; Kostoglodov *et al.* 2003), when the transient displacements in Guerrero exceeded those in Oaxaca. Data from GPS station PINO in western Oaxaca (Lowry 2006) also show the 2004 transient and suggest a slip displacement that is intermediate between that recorded at the sites in Oaxaca and Guerrero (Fig. 5).

Our analysis of the continuous time-series at site OXPE in Oaxaca indicates that transient motion began at 2004.07 (Table 1), the

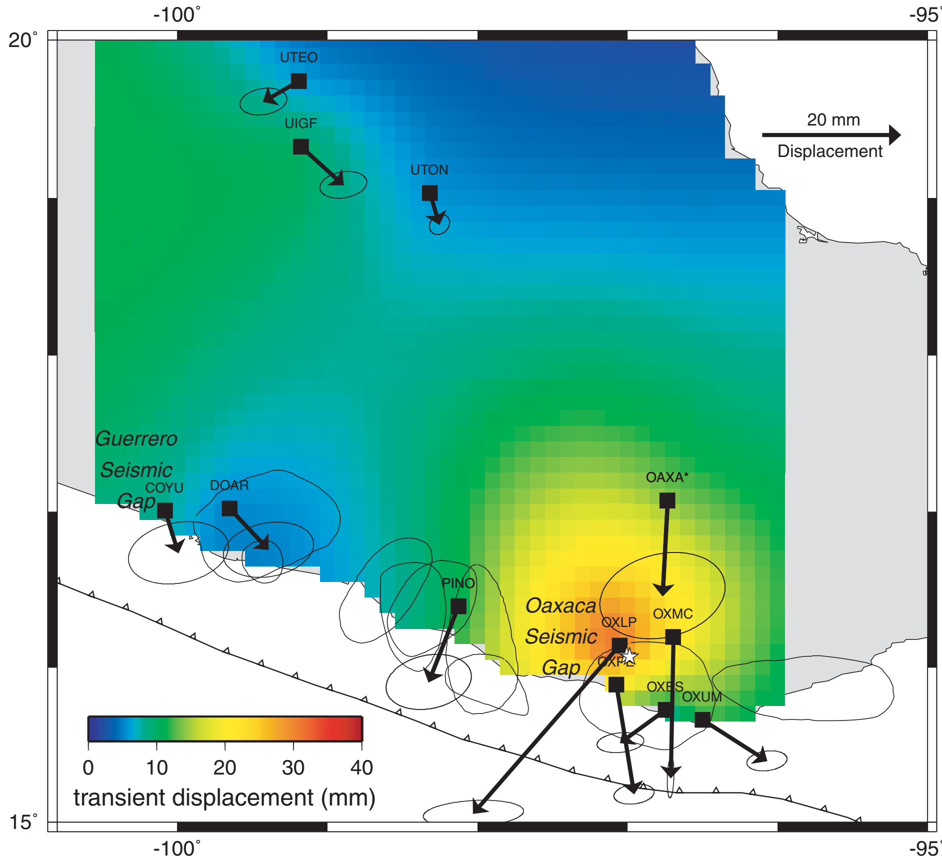

Figure 5. Transient displacements during the 2004 episode determined from hyperbolic tangent fits to the continuous GPS time-series that are shown in Fig. 2. Motions at UNAM proprietary sites PINO and OAXA∗ are from Lowry (2006). The offset at INEGI site OAXA is not available for this time due to a data gap (Fig. 1). Coloured background shows an interpolated fit to the displacement distribution, which increases towards the Oaxaca seismic gap. Stars are locations of moderate 2004 January earthquakes that immediately preceded transient motions.

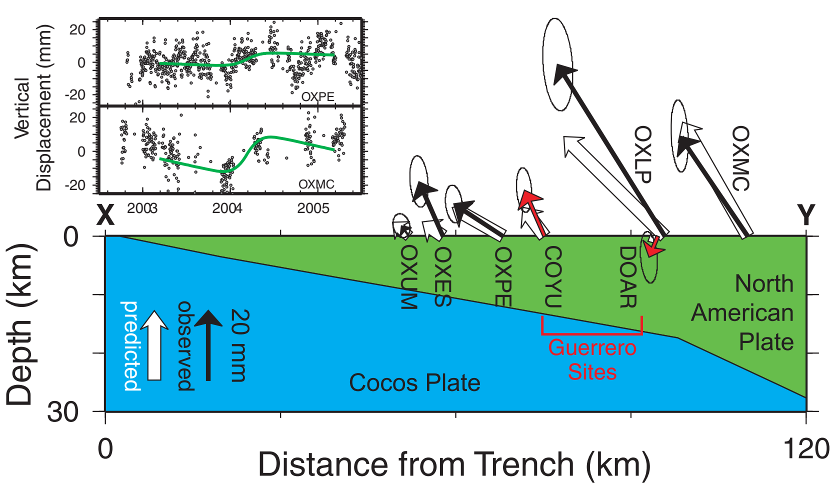

Figure 6. Cross-section perpendicular to the trench showing projected vectors and error ellipses that combine the horizontal and vertical components of the transient slip offsets (observed – solid, modelled – open) during the 2004 slow slip episode. Measurements from Oaxaca are in black, Guerrero in red. Thin line separating the subducting (blue) and overriding (green) plates is the plate interface geometry used in modelling transient slip. Upper left-hand side inset shows vertical component time-series and hyperbolic tangent fit from sites with a small vertical offset (OXPE) and a large vertical offset (OXMC).

same within uncertainties as when motion began at stations COYU and DOAR in Guerrero (Fig. 2c). The lack of any apparent time progression in the onset of transient motion at sites in Oaxaca and Guerrero thus leaves the issue of where transient slip first originated open for debate. In Section 7.1, we discuss in more detail potential scenarios and two lines of evidence, neither conclusive, that suggest transient slip may have originated outside the Guerrero seismic gap.

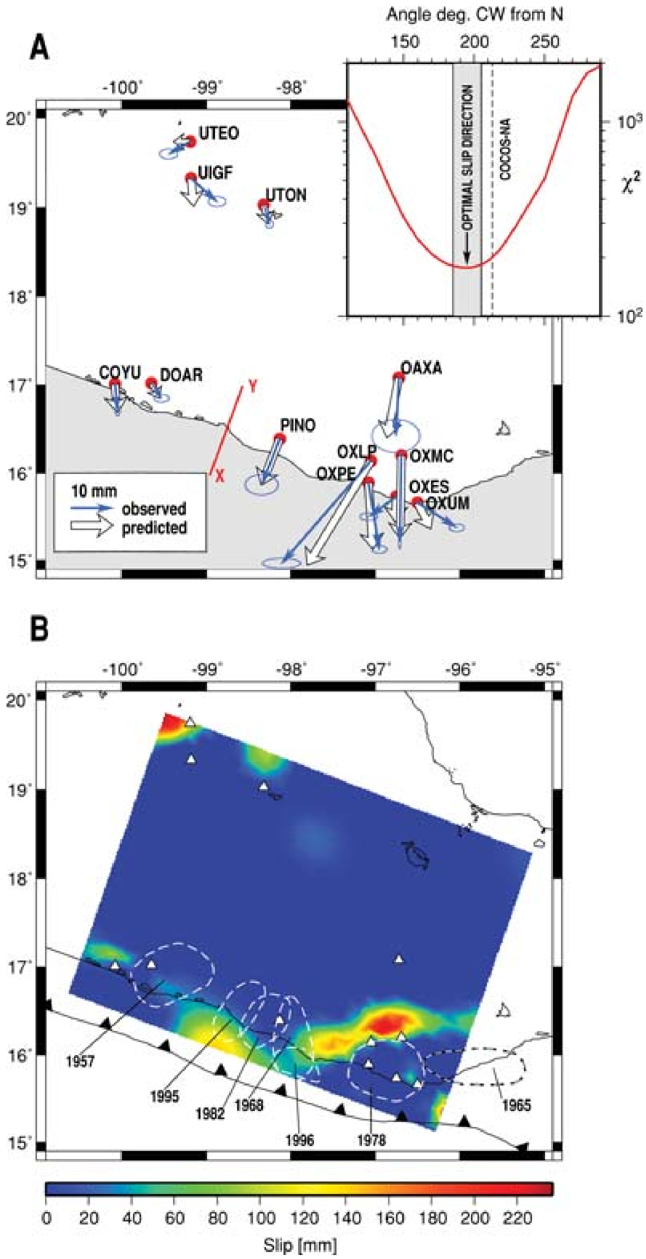

Figure 7. (a) Observed (blue arrows) and estimated (open arrows) offsets during the 2004 transient slip event with 2-D, 1σ uncertainties. Inset shows weighted least-squares misfit χ^2 as a function of the assumed slip direction during the transient. Dashed line indicates Cocos-North America convergence direction predicted by plate circuit closures (DeMets 2001). (b) Location and magnitude of transient slip along the surface projection of the subduction interface depicted in Fig. 3. Dashed lines enclose approximate rupture zones of previous large earthquakes, and triangles indicate locations of GPS stations that recorded the 2004 transient slip event.

5.2 Preferred slip distribution for the 2004 transient event

Fig. 7 summarizes the results for our inversion of the 2004 transient offsets using techniques described in Section 3.3. Repeated inversions for the best overall slip direction (Fig. 7a inset) yields a best direction of N15°E, with minimal trade-off between the estimated slip direction and the smoothing coefficient. This direction is reasonably consistent with the N33°E Cocos-North America convergence direction predicted from plate circuit closures (DeMets, 2001). Fits to the horizontal site offsets (Fig. 7a) are typically within the 2-D, 95 per cent uncertainties that we estimate from our hyperbolic tangent fitting. The good fit to the vertical offsets (Fig. 6), which have little influence on the best-fitting solution due to their large uncertainties, is encouraging and serves as a semi-independent check on the validity of the solution. We investigated the influence of the uncertainties we assigned to the transient offsets by re-inverting the data with more uniform ± 1, ± 2 and ± 4 mm standard errors for the north, east and vertical components of the offsets. The resulting alternative slip distribution (not shown) is remarkably similar to the best-fitting solution (Fig. 7b), indicating that the latter is relatively robust with respect to the relative data weights.

Our preferred slip distribution (Figs 3 and 7b) places most aseismic slip (~180–220 mm) near the Oaxaca GPS stations along the transitional slip zone downdip from the 1978 earthquake rupture zone, with additional but lesser slip (~100–150 mm) extending to shallow regions near the Oaxaca seismic gap. Remarkably, the area of transient slip along the subduction interface extends to the estimated downdip and western edges of the 1978 earthquake rupture zone, but does not extend into it. Measurements at GPS stations OXLP and OXMC (Fig. 7a), which are located above the downdip limit of the 1978 rupture zone, require the transient slip at 97°W to be located deeper than the 1978 rupture zone. Similarly, shallow transient slip from 97.7° to 97.3°W between the eastern limit of the 1968 earthquake rupture zone and western edge of the 1978 rupture zone is required and constrained in location by measurements at sites PINO, OXLP and OXPE. The transient slip that occurred during the 2004 slow slip event was equivalent to the release of 2–3 yr of accumulated Cocos-North America plate convergence at a rate of 70 ± 5 mm yr^{-1} (DeMets 2001). The equivalent moment magnitude of transient slip in this region is $M_w = 7.3$.

The slip described above induces only a minimal (submillimetre) elastic response at sites TOLU, UIGF, UTEO and UTON in the volcanic belt, much smaller than their observed transient motions of 5–10 mm (Figs 2 and 5 and Table 1). In order to fit these distant and yet significant offsets, the inversion places smaller isolated slip patches offshore at 99°–98°W and beneath the Mexican volcanic belt at the northwest corner of the modelled slip area. The sparse network geometry in 2004 for areas outside Oaxaca severely limits our ability to resolve slip patches outside of Oaxaca. We therefore, suspect that the region of apparently high slip at the northwest corner of the subduction interface, deep beneath the Mexican volcanic belt, is a likely artefact of the sparse station distribution. Forward modelling exercises in which we replace the isolated slip patches shown in Fig. 7b with lower magnitude slip (10–20 mm) over a much broader area of the subduction interface between the volcanic belt and the Oaxaca GPS network fit the observed transient offsets for sites in the volcanic belt nearly as well.

Our preferred slip distribution thus consists of (1) slip along a transitional zone that extends ~100 km parallel to the trench and ~50 km downdip, (2) additional shallower slip in the Oaxaca seismic gap and (3) lesser, more poorly resolved slip that affected the remaining subduction interface. A discussion of the possible implications of shallow aseismic slip in the Oaxaca seismic gap is reserved for Section 7.

6 TRANSIENT SLIP IN EARLY 2006: EVIDENCE FOR SLIP INITIATION IN OR NEAR OAXACA

The GPS coordinate time-series for 10 stations in southern and central Mexico show that significant transient motions began in early

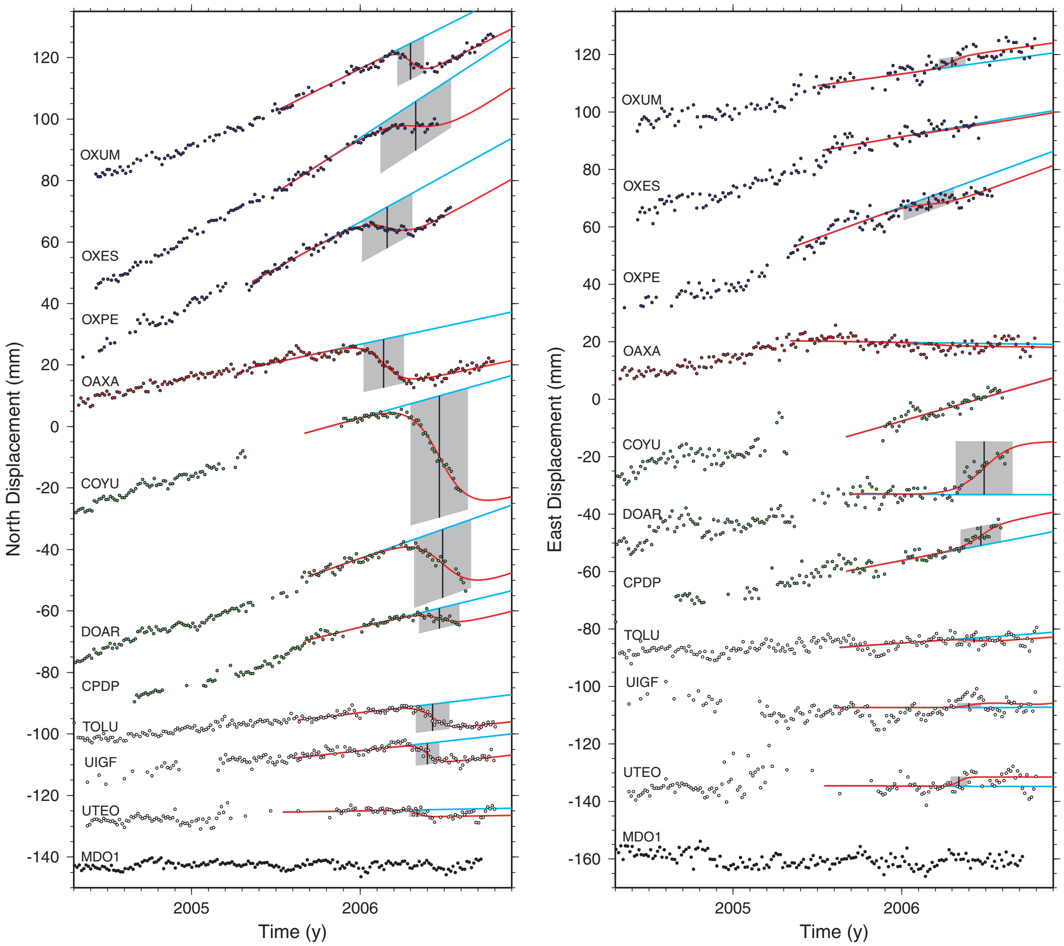

Figure 8. North (left-hand side) and east (right-hand side) components of continuous GPS time-series from various sites illustrating transient deformation during the 2006 episode. Red curves show hyperbolic tangent fits, with grey area and vertical black line showing τ and T_0, respectively. Blue curves show linear fits before the transient occurs. The north component of the time-series (left-hand side) clearly shows an earlier onset for sites OAXA, OXPE and to a lesser degree, OXES and OXUM in Oaxaca than at sites in Guerrero (COYU, CPDP and DOAR) and in the Mexican volcanic belt (TOLU, UIGF and UTEO). Layout is similar to Fig. 2, but with five-sample running mean applied. Site motions are specified relative to the North American plate.

2006 (Figs 8–10) and were still occurring at sites in Guerrero as of 2006 mid-September. Sections 6.1–6.3 describe initial observations of this complex transient for sites in Oaxaca and Guerrero, with the primary focus on the evidence that this slip transient originated outside the Guerrero seismic gap. Modelling of the space–time history of slip along the subduction interface using Network Inversion Filter software (Segall & Mathews 1997; McGuire & Segall 2003) is deferred to a future paper.

6.1 Deformation pattern and timing

Significant transient motions were first recorded at stations OAXA and OXPE in the first week of January in 2006 (Table 1, Figs 8–10) and was followed by the onset of transient motions at progressively later times at stations farther away (Figs 8 and 10). Total slip displacements at all four sites in Oaxaca were 10–20 mm (Figs 8–10), with the most motion occurring at the site farthest from the trench (OAXA).

Fig. 9 shows a time-series of monthly average locations for sites in Oaxaca relative to the North American plate interior (Fig. 9a) and after removing the contribution of long-term steady interseismic strain (Fig. 9b). All four Oaxacan sites that were recording during this period moved northeast towards the plate interior from early 2005 until August of 2005, representing the influence of steady or near-steady strain accumulation from locked areas of the subduction interface. During September and October of 2005, the direction of motion at three of the four sites (OAXA, OXES and OXPE) changed ∼90° counter-clockwise, to the northwest. The reason for this change is unknown, although a $M_w = 5.8$ earthquake on 2005 August 14 ruptured the subduction interface close to site PINO and immediately west of the Oaxaca GPS network just weeks before the observed westward change in site motions. During November and December of 2005, site OAXA moved gradually westward and then began moving rapidly southward in early 2006 (Fig. 9b).

The surface deformation that occurred in response to the transient slip in early 2006 was dominated by southward motion of the GPS sites towards the trench (Figs 9b and 10). Transient motion at OAXA ended by late March of 2006, indicating that transient slip lasted for ∼3 months in this region (Table 1). Transient motion at sites OXPE, OXES and OXUM ended progressively later, but had similar event durations (Table 1). Displacements at sites OAXA, OXPE and OXUM ended by April of 2006, but appear to have continued up until at least June of 2006 at OXES.

Transient motion at sites in Guerrero and the volcanic belt first occurred at site COYU in early to mid-March of 2006 (Table 1 and

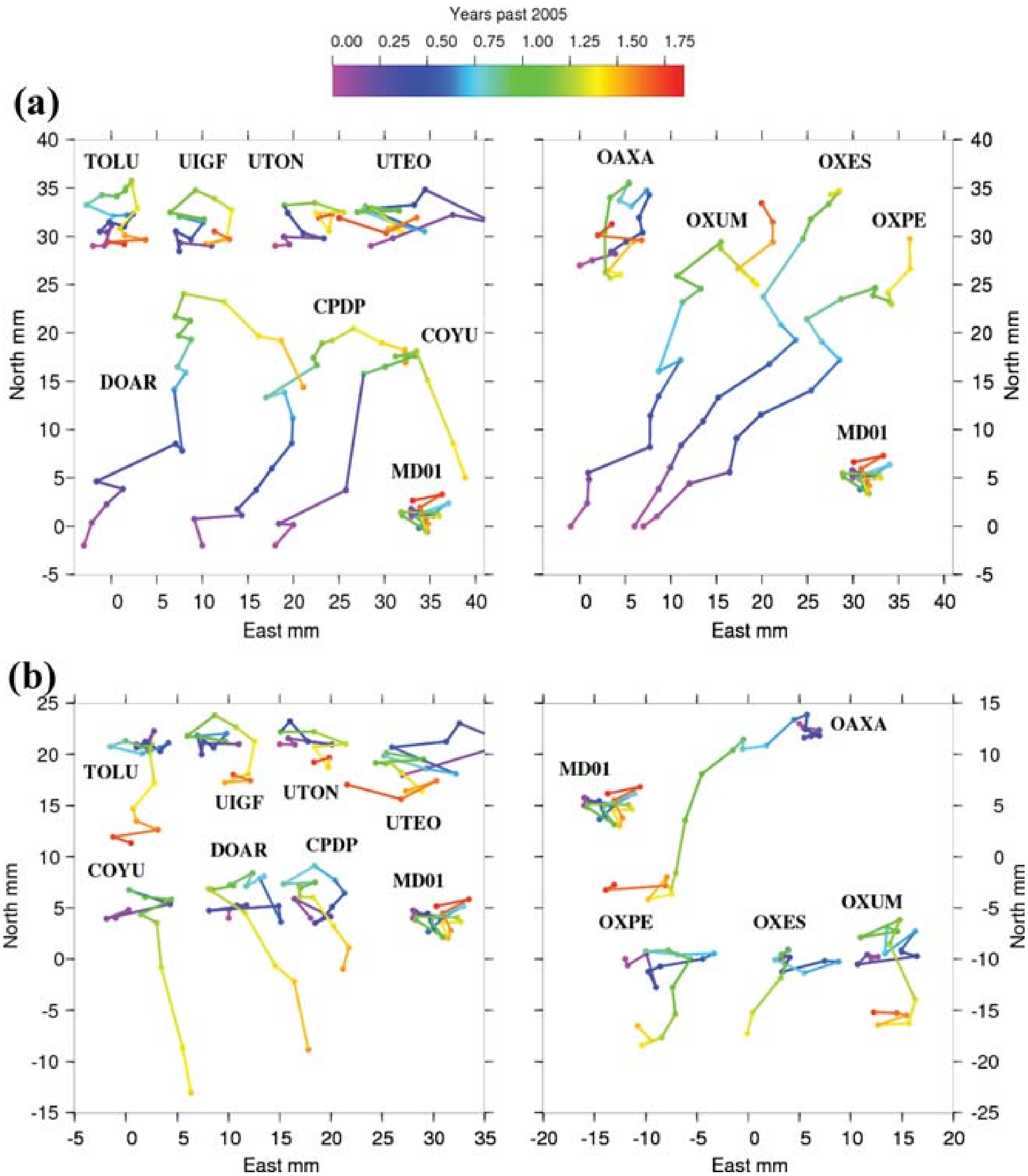

Figure 9. GPS station displacement time-series for the period 2005.0–2006.8. Colour scale at upper right-hand side specifies time-progressive colour coding along the site paths. Each point shows the 30-d-mean location for a given site, with initial site locations offset for clarity. Motion of site MDO1 in southern Texas is indicative of the noise in the monthly average locations. Site paths rely on same data as are shown in Fig. 8. (a) North American plate motion is removed from the motion of each site—sites thus generally move northeastward through time towards the plate interior due to elastic strain accumulation from the Middle America trench. (b) Steady northeastward strain accumulation at each site is removed to accentuate the transient motion.

Figs 8–10) and was followed within 1 month by the initiation of transient motion at other sites in Guerrero and the volcanic belt. During the year that preceded the 2006 transient, the motions of the sites in Guerrero and the volcanic belt were generally northeastward towards the plate interior (Fig. 9a) at rates that decreased with increasing distance from the Pacific coast (Fig. 8). Site motions during the slip transient included small, but significant eastward components at two of the three coastal sites in Guerrero (CPDP and DOAR in Figs 9b and 10). Transient displacements varied from 20–30 mm at coastal sites COYU and DOAR to 5–10 mm at sites in the volcanic belt (Fig. 8), with the former representing minimum displacement estimates given that transient motion at the coastal sites in Guerrero had not yet ceased at the time we completed our analysis.

Based on the onset times of transient motion described above, slow slip in the Oaxaca region began ∼2.5 months earlier than slow slip in Guerrero and the volcanic belt. Site motions in Oaxaca were generally towards the south–southwest, whereas site motions in Guerrero were generally towards the south–southeast to southeast (Fig. 10). The temporal pattern defined by the onset of transient displacements (Fig. 10) suggests that slip originated somewhere beneath or near Oaxaca. The later onset of deformation at site OXUM at the eastern edge of the Oaxaca network suggests that transient slip propagated to the east. Whether slip also propagated westward and triggered later transient motion at sites in Guerrero and the volcanic belt is unknown given the lack of public domain data from GPS stations between Oaxaca and Guerrero.

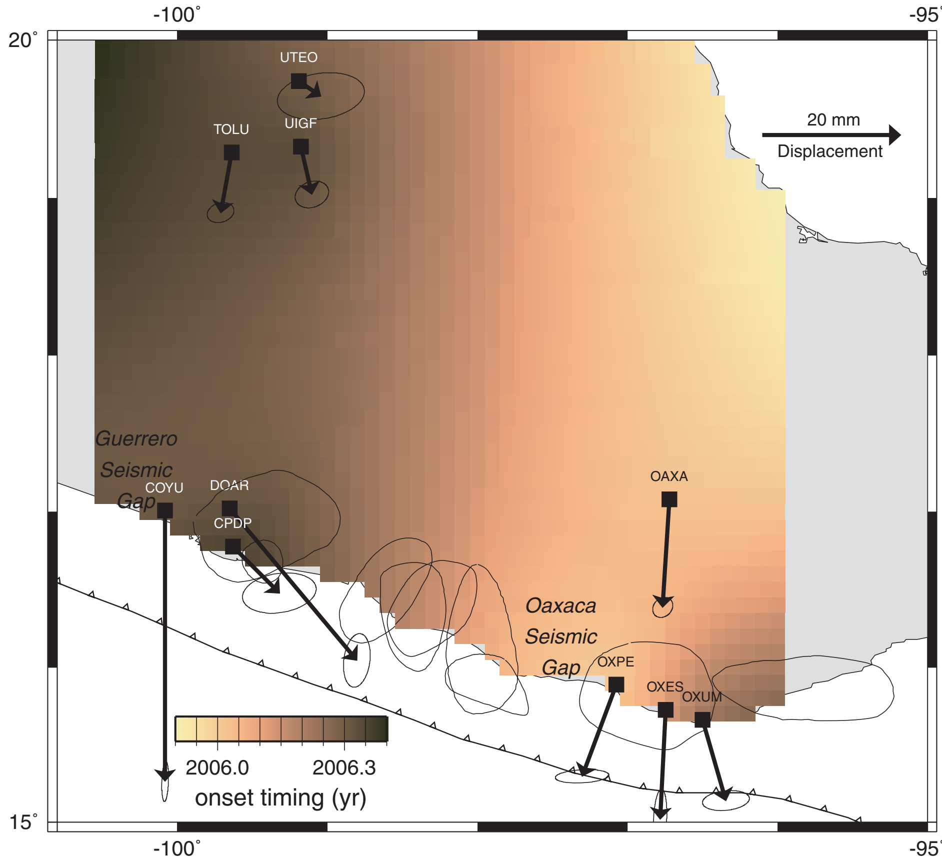

Figure 10. Vector displacements and timing of the 2006 transient episode from hyperbolic tangent fits to GPS coordinate time-series shown in Fig. 9. Site motions are specified relative to the North American plate.

6.2 Preferred slip distribution for the 2006 transient event

Given that the 2006 transient event ended in Oaxaca by mid-2006, we inverted the offsets from the four Oaxacan stations (Fig. 11a) that were operating during this transient to estimate the approximate location and magnitude of the transient slip, assuming once again that the slip originated along the subduction interface. The optimal slip direction in 2006 (inset to Fig. 11a) was the same as that for the 2004 transient event, and the slip during both events was located between the Pacific coast and inland site OAXA. The slip distributions and maximum slip magnitudes however differ substantially. We attribute these differences to the poorer station coverage in 2006, particularly at stations OXLP and OXMC, where our Ashtech receivers both suffered hardware failures. Without measurements from these two sites, the deformation gradient between OAXA and the coast is poorly constrained and our ability to resolve the location of slip along the subduction interface is significantly impaired. This specific example underlines the need for improved continuous GPS site coverage south of the Mexican volcanic belt.

7 DISCUSSION AND INTERPRETATIONS

7.1 Evidence for the origination of transient slip in or near Oaxaca

The results reported above expand the spectrum of observed episodic slip behaviour in southern Mexico in several respects. Transient slip in 2006 began two or more months earlier in Oaxaca, demonstrating that transient slip can originate along the subduction interface in areas hundreds of kilometres from the Guerrero Seismic Gap. The evidence that the 2006 event initiated outside of Guerrero and may have triggered moderate-to-large amplitude transient slip near the Guerrero Seismic Gap months afterward expands the range of potential triggers for eventual large subduction thrust earthquakes in Guerrero and elsewhere along the Middle America trench, provided that slow slip events are capable of triggering seismogenic slip at shallower depths.

In 2004, the near simultaneity of the onset of transient motions at sites in Oaxaca and Guerrero precludes a simple determination of where that transient slip originated. Two observations however suggest that transient slip may have originated close to Oaxaca or possibly within the Oaxaca seismic gap. The onset of transient motions in 2004 was preceded only 3–6 d earlier (Fig. 2c) by a pair of moderate (M_w 5.1, M_w 5.5) earthquakes that occurred 1.5 hr apart on 2004 January 13 at a depth of ∼26 km (Engdahl *et al.* 1998; Engdahl & Villasenor 2002, and subsequent updates). A projection of the earthquake hypocentres onto the subduction interface (Fig. 3) places these two earthquakes near the downdip end of the seismogenic zone, close to the eastern edge of the Oaxaca Seismic Gap. The GPS site closest to these epicentres, OXLP (Fig. 5), is located only 10 km WNW of the earthquake epicentres and recorded larger transient motions in 2004 than the other nine stations where this transient was recorded. The timing of these two earthquakes with respect to the onset of transient motions, their locations near the downdip edge of the seismogenic zone, and the proximity of the region of greatest transient surface deformation to the two earthquake

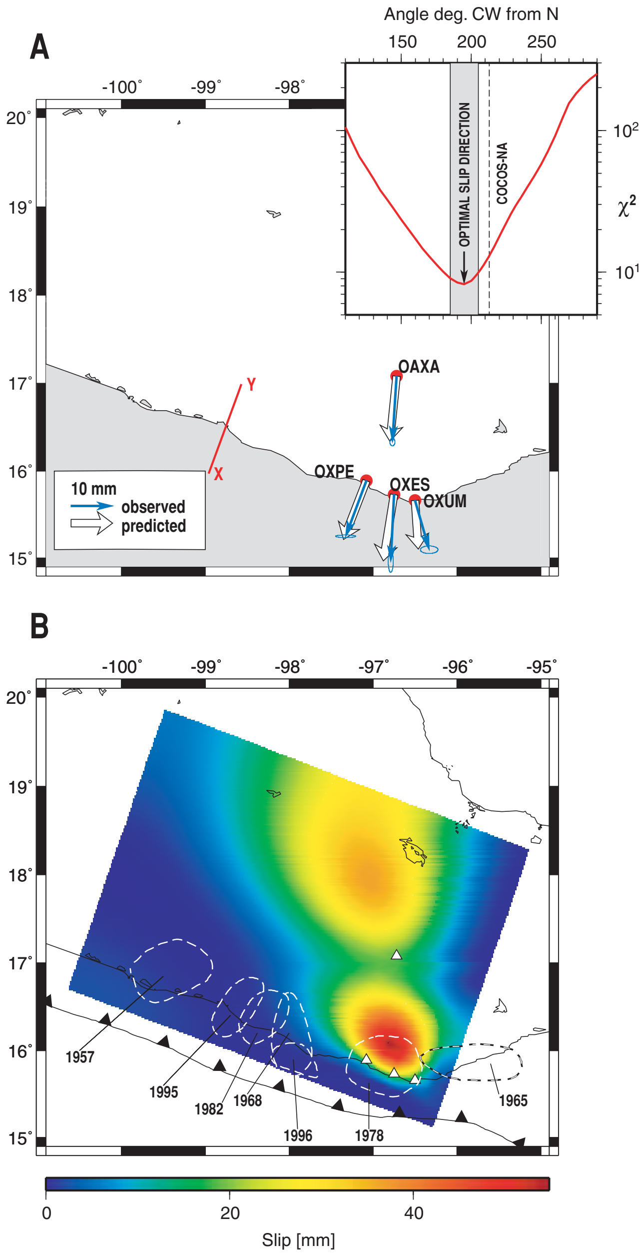

Figure 11. Inversion results for the 2006 transient slip event. Layout is as in Fig. 7. (a) Observed and estimated offsets with uncertainties. (b) Location and magnitude of transient slip. Triangles indicate locations of GPS stations in the Oaxaca region that are inverted for the 2006 transient slip event.

epicentres suggest that these earthquakes played a role in triggering transient slip. If true, this indicates that transient slip originated close to the Oaxaca Seismic Gap and either propagated rapidly outward or induced stress changes along the transitional area of the subduction interface in Guerrero that enabled the onset of transient slip there.

Alternative scenarios for the near-simultaneous initiation of slow slip in 2004 (aside from sheer coincidence) include that the two events were initiated near-simultaneously by the same trigger, or the slip propagated extremely rapidly along strike. The rapid propagation scenario would be more similar to that of an earthquake, quite different from what has been reported for episodic tremor and slip in other subduction zones where correlated GPS and seismic signals suggest slow slip propagates at ∼10 km d^{-1} (Obara 2002; Rogers & Dragert 2003). While we cannot currently distinguish between these scenarios, recently installed seismic networks in Guerrero and Oaxaca have recorded non-volcanic tremor (Brudzinski *et al.* 2007; Payero *et al.* 2007), whose source locations should provide an indicator to help distinguish where slow slip is originating. Identifying whether the initial part of the episode is localized should provide a better understanding of how ETS initiates and what controls its origin.

Observations at stations CAYA and OAXA for annual slip transients from 1998 to early 2001 (Fig. 4) yield transient motions that point towards the region between Guerrero and Oaxaca. Only the large-magnitude 2002 transient slip event clearly originated in Guerrero (Kostoglodov *et al.* 1996; Yoshioka *et al.* 2004). Together, these results suggest that transient slip in southern Mexico frequently originates outside the Guerrero seismic gap. Although the available data are still too limited in space and time to determine whether transient slip originates in a limited number of source regions outside of Guerrero or whether the conditions for the initiation of slow slip exist widely along the downdip, frictionally transitional areas of the Cocos-North America subduction interface, we favour the latter proposition. Such a hypothesis is supported by a growing number of observations of slow slip from other subduction zones (Douglas *et al.* 2005; Brudzinski & Allen 2006; Ohta *et al.* 2006; Pritchard & Simons 2006; Wallace & Beavan 2006).

7.2 Timing and recurrence of transients

Based on the long GPS time-series at site OAXA and data from nearby continuous sites in Oaxaca, significant transient slip appears to have occurred nine or possibly 10 times (depending on the detection threshold we adopt) during the 13 yr for which we have data (Fig. 1). In the years that transient slip occurs, its timing has been remarkably predictable, with 9 of the 10 slip episodes beginning in either December or January. The onset of transient motions at OAXA bears no obvious relationship to variations in fault-normal and fault-parallel stresses that are modulated by Chandler wobble (Shen *et al.* 2005), which instead act on a 14 month cycle. Using calculated variations in the tensional fault-normal component of stress and thrust-inducing fault-parallel stress component induced by pole-tides, Shen *et al.* (2005) show that the 1998 and 2002 transient events in Guerrero both coincided with the ascending phase of fault-parallel shear stresses. In contrast, the transients measured in Oaxaca in early 1998 and 1999 occurred during a period of descending pole-tide stresses, contrary to the hypothesis that pole-tides trigger these transients. Moreover, the transient in 2000 occurred during a minor peak in the stresses. Only the transient that occurred in late 2001/early 2002 clearly occurred during a period when the components of stress conducive to fault slip were increasing.

Using data from different GPS stations in Mexico, Lowry (2006) has independently concluded that transients in this region are not strongly correlated to stress variations induced by pole tides and instead proposes that annual variations in the surface water load in southern Mexico can be invoked to explain the timing of most transients in that region and possibly elsewhere. The remarkable regularity of the onset of transient motions at site OAXA in January and hence 12-month periodicity in southern Mexico supports Lowry's hypothesis.

7.3 Evidence for disjoint areas and times of seismogenic and transient slip

Evidence that slow subduction slip events occur in the previously hypothesized frictional transitional zone downdip from the seismogenic zone (e.g. Dragert *et al.* 2001) has led to suggestions that transient slip episodes might rapidly load the subduction interface updip and hence potentially trigger large thrust earthquakes (Mazzotti & Adams 2004). Our results contribute new information to our still incomplete understanding of the spatial and temporal relationship between slow slip events and large subduction earthquakes. In the temporal domain, nearly all slow slip episodes in southern Mexico since the mid-1990s have initiated in either December or January. Assuming that this was also the case in the past, which follows from Lowry's (2006) hypothesis that 12-month periodicity is caused by annual variations in the surface water load, then both the $M = 7.3$, 1968 August 2 and the $M = 7.6$, 1978 November 29 Oaxaca earthquakes occurred months after the presumed initiation of any slow slip in 1968 and 1978. These observations suggest that transient slip does not cause seismogenesis over timescales as short as days to weeks, as might be expected if transient slip episodes created velocity perturbations along the subduction interface that triggered frictional instabilities and hence rupture in the velocity-weakening, updip areas of the subduction interface. The available evidence, namely that a pair of moderate (M_w 5.1, 5.5) earthquakes ruptured the downdip end of the seismogenic zone immediately east of the Oaxaca seismic gap shortly before the onset of transient slip in 2004, suggests the converse, that earthquakes are capable of triggering slow slip over short timescales.

Our results are more definitive regarding the separate source areas of slow slip episodes and megathrust earthquakes. The lack of overlap between the region of transient slip in 2004, as estimated from our inversion (Fig. 7b), and the limits of seismic slip during shallow-thrust earthquakes, as estimated from contemporary seismic observations, strongly suggest that these processes occur in separate but adjacent areas. The best-constrained area of slow slip in 2004 curls remarkably around the edge of the 1968 rupture zone and halts at the edge of the 1978 rupture area, near the tip of the 1996 rupture zone. Slow slip thus does not appear to be limited to a deeper, depth-limited zone of transitional frictional properties, but also appears to accommodate some fraction of the plate convergence along parts of the subduction interface that surround former megathrust rupture zones.

The apparent extension of aseismic slip in 2004 to seismogenic depths in the Oaxaca seismic gap (97.7°–97.3°W in Fig. 7b) raises the question of whether shallow transient slip in this area accommodates enough of the plate convergence to preclude major thrust earthquakes. If so, the Oaxaca seismic gap would either arrest or slow down the along-strike propagation of shallow-thrust earthquakes that originate northwest or southeast of the seismic gap, thereby limiting the potential moment release of earthquakes in this area. Better station coverage is needed to confirm whether transient slip is occurring at such shallow depths. Identification of non-volcanic tremor source locations with new seismic networks should also help to distinguish where slow slip is originating.

7.4 Comparison to slip transients in Cascadia

Finally, we briefly discuss the different characters of transient slip observed in southern Mexico and Cascadia. Typical maximum surface displacements in Mexico are ∼20–50 mm (Lowry *et al.* 2001; Kostoglodov *et al.* 2003; Larson *et al.* 2004), roughly an order-of-magnitude larger than has been recorded in Cascadia (e.g. Dragert *et al.* 2001; Miller *et al.* 2002; Szeliga *et al.* 2004). In addition, transient slip may have included parts of the seismogenic zone in Guerrero in 2002 (Iglesias *et al.* 2004; Yoshioka *et al.* 2004) and in Oaxaca in 2004, as reported above. In contrast, no evidence has yet been found for the updip propagation of slow slip into the seismogenic zone of Cascadia.

We surmise that the significantly larger transient slip measured in Mexico relative to that recorded in Cascadia is at least partly related to the differing subduction geometries and tectonic settings of these two regions. Trench-normal convergence rates in southern Mexico range from 55 to 75 mm yr^{-1}, approximately a factor of two faster than along the Cascadia subduction zone. Relatively flat subduction occurs beneath large areas of southern Mexico (Pardo & Suarez 1995), placing large areas of the subduction interface at thermal conditions potentially conducive to transitional frictional behaviour (Manea *et al.* 2004). In comparison to Cascadia, where subduction occurs at a steeper angle, significantly more (by a factor or two or more) elastic strain is recharged annually by frictional coupling across transitional areas of the Mexican subduction interface and is thus available for release by transient slip.

8 CONCLUSIONS

Data from 12 continuous GPS stations in southern Mexico define nine distinct episodes of transient slip from 1993 to 2007, including previously unreported transient slip episodes in early 1995 and 2006. Transient slip in southern Mexico affects widespread areas considering that all transient slip episodes recorded in Oaxaca City were also recorded at a GPS site ∼400 km away in the state of Guerrero after measurements began there in early 1997.

For the 2004 slow slip event, displacements of more than 20 mm were recorded at stations in the Oaxaca GPS array, a factor of 2–3 larger than at sites in Guerrero and the Mexican Volcanic belt, despite similar onset times. Elastic half-space modelling of the 2004 displacements indicates that most slip was focused beneath Oaxaca in deeper, presumably non-seismogenic areas of the subduction interface, but that slip also may have extended significantly updip into a seismic gap along the Oaxaca coast. The best-fitting model is also able to explain transient vertical offsets of up to 50 mm observed during this event. Shortly before the onset of transient slip in 2004, a pair of moderate (M_w 5.1, 5.5) earthquakes ruptured the downdip end of the seismogenic zone immediately east of the Oaxaca seismic gap, suggesting a possible relationship between the two. The close correspondence between the updip and western edges of the zone of transient slip along the subduction interface and the edges of the 1978 earthquake rupture zone suggest that there are downdip and along-strike limits on the geographic extent of seismic rupture and hence seismic moment release for a single shallow-thrust earthquake in this region. More data and better station coverage are needed to confirm whether transient slip extends to shallow depths in the Oaxaca seismic gap.

In 2006, transient slip began 1–3 months earlier in Oaxaca than in other areas, providing the best evidence to date for the existence of source regions for transient slip outside the potentially hazardous Guerrero seismic gap, where large amplitude transient slip originated in 2002. An inversion of offsets in 2006 for four sites that were active at the time indicates that the transient slip was focused along the subduction interface between the coastal GPS stations and inland site OAXA, similar to 2004. A more precise determination of the slip location is however severely limited by the poor station geometry in 2006, a situation now being rectified by the installation of additional continuous sites in southern Mexico.

ACKNOWLEDGMENTS

This work was supported by NSF grants EAR-0104299 and EAR-05510887 to C. DeMets, EAR-0510812 to M. Brudzinski and CONACyT grant 33121-T, an UNAM-PAPIIT grant and grants IN121505 and IN123504 to E. Cabral-Cano. We acknowledge invaluable field support from Oscar Díaz-Molina, Gerardo Cifuentes-Nava and Esteban Hernández-Quintero, and are also grateful to INEGI and UNAVCO for access to their data archives. We appreciate helpful discussions with W.-P. Chen, S. Holtkamp and T. Lowry, and thank Roland Burgmann and Jeff Freymueller for reviews that caused significant improvements in the original manuscript. Data from NSF-sponsored sites OXLP and OXMC are archived at UNAVCO.

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