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The 2006 aseismic slow slip event in Guerrero, Mexico: New results from GPS

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[1] Crustal deformation measurements from Guerrero, Mexico were made with continuous GPS instrumentation. This network spans 75 km along the coast and a 275 km transect from the coast to Mexico City, which is perpendicular to the Middle America trench. A large aseismic slip transient occurred from April to December 2006, yielding horizontal displacements of nearly 6 cm in the direction opposite to that recorded interseismically. This transient slip episode closely follows a series of ~M5 deep intraplate events that occurred in the northwestern portion of the Guerrero region. Both horizontal and vertical displacements are inverted for the Guerrero GPS network to determine slip along the subduction interface. Using a simple fault model that accommodates changes in the subduction zone geometry, it is found that slip is concentrated on interior fault patches, and propagated to the southeast. This slip event has a minimum equivalent Mw of 7.5. **Citation:** Larson, K. M., V. Kostoglodov, S. Miyazaki, and J. A. S. Santiago (2007), The 2006 aseismic slow slip event in Guerrero, Mexico: New results from GPS, *Geophys. Res. Lett.*, *34*, L13309, doi:10.1029/2007GL029912.

1. Introduction

[2] Aseismic slow slip events (SSE) in subduction zones were first reported in Japan [*Heki et al.*, 1997; *Hirose et al.*, 1999; *Ozawa et al.*, 2002], with a variety of non-linear deformation patterns observed with data of the large Japanese GPS network. High quality tiltmeters and seismic instrumentation provides additional information about SSE in Japan that is not visible in the GPS records [*Hirose and Obara*, 2006; *Ide et al.*, 2007]. In addition to Japan, many geodetic studies of transient slip have been focused on Cascadia [*Dragert et al.*, 2001; *Melbourne et al.*, 2005]. In this subduction zone, small (~5 mm) quasi-periodic transient slip episodes that last several weeks have been observed. Following the discovery of deep non-volcanic tremor (NVT) in Japan [*Obara*, 2002], similar NVT was observed and then correlated with Cascadian SSE [*Rogers and Dragert*, 2003], resulting in dedicated seismic experiments to recover the spatial and temporal complexity of transient slip [*McCausland et al.*, 2005; *Kao et al.*, 2007].

[3] SSE has been observed in other subduction zones, for example in Mexico [*Lowry et al.*, 2001; *Kostoglodov et al.*, 2003], New Zealand [*Douglas et al.*, 2005; *Wallace and Beavan*, 2006], Alaska [*Ohta et al.*, 2006] and Costa Rica (Tim Dixon, personal communication, 2007). In each of these cases the observed displacements (1 to 6 cm) are larger and more temporally complicated than what has been observed in Cascadia. It is not clear why this is the case. Since many of these regions lack the dedicated seismic instrumentation available in Japan and Cascadia, there have been fewer data to characterize the relationship of tremor and slip. And since the larger slip events have not occurred as often as the smaller Cascadian transients, there is no easy way to predict when they will occur. A large transient slip event recently occurred in Guerrero, Mexico, which allows us an opportunity to study how large aseismic slip propagates in this subduction zone and compare it with transients previously observed in the region.

2. Tectonic Background of Guerrero and GPS Measurements

[4] The Guerrero (Figure 1) region is located on the southern Mexican coast along the Cocos-North America plate boundary. Convergence rates predicted from NUVEL1-A vary from 5.2 to 5.9 cm/yr at N33E. This is slightly oblique to the trench and results in some right-lateral motion. The geometry of the subducting slab has been evaluated by waveform modeling and locating hypocenters [*Pardo and Suarez*, 1995] and gravity anomaly modeling [*Kostoglodov et al.*, 1996]. The slab megathrust has an average dip of ~12 degrees from the trench to ~150 km inland and then becomes almost subhorizontal beneath the continental lithosphere at a depth of ~40 km. The last large subduction thrust earthquake in northwest Guerrero occurred in 1911. Because of its close proximity to the capital of Mexico, assessing seismic potential for the region is a high priority. A strong motion network was installed in 1985. The seismicity catalog for the region is compiled by the Servicio Sismologico Nacional (SSN), which uses local and regional travel times to localize most of the seismic events with M > 3.5.

[5] SSE was first observed in Guerrero with GPS in 1998 at station CAYA (Figure 1) [*Lowry et al.*, 2001]; this same transient could also be seen at a site 275 km inland [*Larson et al.*, 2004]. Stations ACAP, IGUA, YAIG were installed along a transect perpendicular to the coast in 2000 and were able to observe the much larger 2001–2002 transient [*Kostoglodov et al.*, 2003]. Stations that had been installed to the northwest (ZIHP) and southeast (PINO) of this transect made it possible to determine the speed, ~2 km/day,

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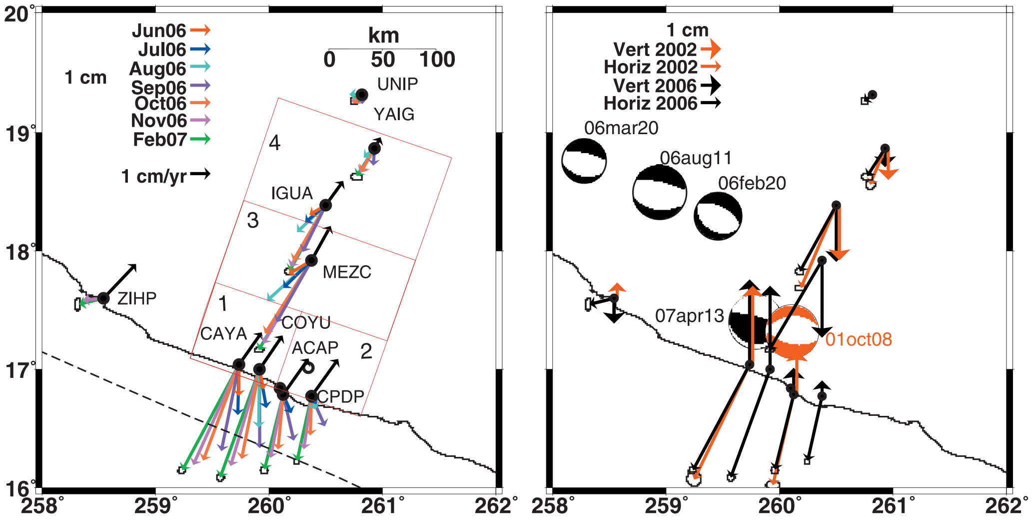

Figure 1. (left) Continuous GPS stations discussed in this study are shown as black circles. Not shown are station ACYA (5 km from ACAP) and DOAR (open circle northeast of ACAP). Surface projections of fault segments used in this analysis are outlined in brown and numbered. Middle America trench location shown as a dashed line. Cumulative displacements for the 2006 transient are shown at monthly intervals and for February 2007. Secular deformation rates relative to North America are shown in black. (right) Comparison of cumulative displacements for the 2002 and 2006 SSE (slow slip event). Horizontal uncertainties are one standard deviation. Vertical uncertainties (not shown) are approximately three times larger than horizontal uncertainties. Harvard CMT solutions also shown.

with which this transient propagated along the coast. Since then, six new sites have been installed in or near Guerrero (COYU, CPDP, DOAR, MEZC, ACYA, and UNIP). Although there are observation gaps at PINO and ZIHP, the other sites in Figure 1 clearly observe the transient slip episode in 2006 that is the focus of this paper.

3. GPS Analysis

[6] GPS data from January 1, 2000 thru February 17, 2007 were analyzed with the GIPSY software [*Lichten and Border*, 1987] using the JPL Earth orientation, clock, and orbit products [*Zumberge et al.*, 1997]. One station position is estimated for each site on each day using an elevation angle cutoff of 12 degrees. The troposphere is estimated as a random walk with azimuthal gradient terms [*Bar-Sever et al.*, 1998]. Each receiver clock is estimated as a white noise process. The pseudorange widelaning technique of *Blewitt* [1989] is used for ambiguity resolution. Ocean loading model FE2004 [*Lynard et al.*, 2006] was evaluated and applied to data from each site. Positions are initially defined in ITRF2000 [*Altamimi et al.*, 2002]. While the precision of the station latitudes is similar to previous publications [*Kostoglodov et al.*, 2003; *Larson et al.*, 2004], using lower elevation angle data and tropospheric gradients has significantly improved longitude and height estimate precision. The improvement in precision is most marked in the last three years. This is presumably because of improved analysis strategies used to estimate the precise orbits, along with the increase in the number of GPS satellites in the constellation.

[7] The transient becomes clearly visible in the position time series in April 2006 (Figure 2 and auxiliary material Figure S1[1]). The character of the transient signal is first examined in the position estimates. In order to remove common-mode errors, baseline components relative to a GPS site on stable North America, MDO1 (McDonald Observatory, Texas) are used. The steady-state station velocities (shown in black in Figure 1) are determined from data collected between 2003.5–2006.25, and put into a North American fixed frame via its plate prediction from ITRF2000 [*Altamimi et al.*, 2002]. Cumulative displacements relative to that detrended time series were estimated by averaging one week of observations at the beginning of each month between April and November 2006 (Figure 1) and then finally on February 1, 2007. The most striking feature early in the transient is the presence of southwesterly deformation at IGUA and MEZC contrasted with southeasterly motion at the coastal sites CAYA and COYU. Subsequently the interior sites IGUA and MEZC show cumulative displacements that are nearly perpendicular to the interseismic direction. Eventually cumulative displacements at the coastal sites also becomes opposite to the interseismic direction, with some rotation and decrease in amplitude as the transient reaches CPDP (50% amplitude decrease relative to CAYA). As shown in the right portion of Figure 1, the vertical signal of this transient is also significant, with nearly 4 cm uplift at CAYA and an equivalent amount of subsidence at the inland site MEZC.

[8] Seismicity ($M \geq 4.0$, SSN catalog) in 2005 and 2006 is shown in auxiliary material Figure S2. There is a visible increase of seismicity in the area of Costa Grande of Guerrero where the main transient slip (CAYA, COYU) took place. In Figure 1, the epicenters and focal mechanisms of relatively large normal intraplate events that occurred in 2006 are shown: a M_W 5.2 (February 20) and 4.9 (March 20), and Mw 6 (August 11). The SSE was followed by a Mb 6.0 thrust event on April 13, 2007. The earlier earthquakes are close to the time of the transient first being observed at MEZC (April). *Franco et al.* [2005] showed

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL029912.

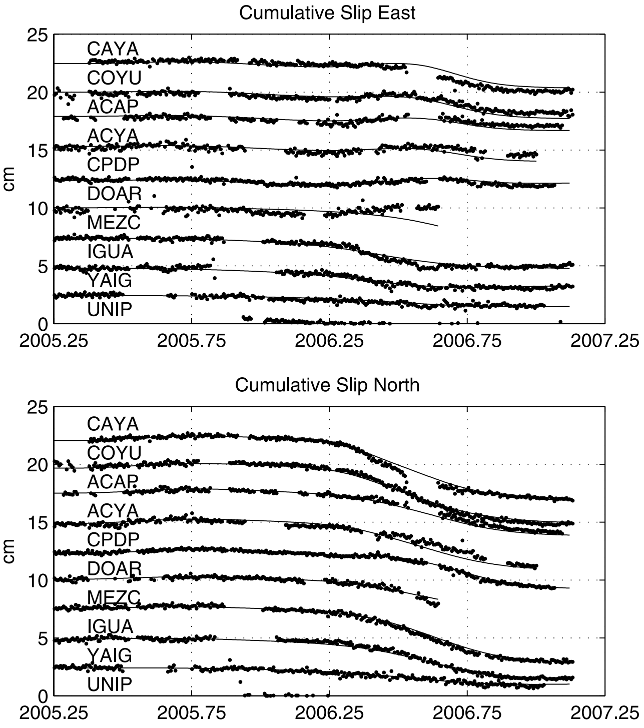

Figure 2. East and north component cumulative slip values (dots) with interseismic slip rate removed. Network Inversion Filter (NIF) model is given by the straight line. The vertical component is given in the auxiliary material.

that the beginning of the 2001–2002 transient was followed by a shallow normal event (Mw5.9), this one located closer to COYU (Figure 1). For the 2006 SSE, an increase of the number of low magnitude events is found by comparison with those observed in 2005.

4. Modeling the 2006 Event

[9] The time series have been modeled using the Network Inversion Filter (NIF) [*Segall and Matthews*, 1997; *McGuire and Segall*, 2003]. The NIF was developed to detect and model aseismic slip. It is based on a recursive Kalman filter algorithm and can model station positions as a stochastic process. It models position time series rather than baseline components. One can also estimate a common-mode error term each day which is important for removing reference frame errors [*Miyazaki et al.*, 2003]. In general, fault slip in Guerrero will include both steady-state and transient components, therefore before using the NIF the steady-state (secular) velocities were removed for each site using the data between 2003.5 and 2006.25. The data before 2003.5 have large gaps and some influence of transient slip episode in 2002 and early 2003. Because of data outages previously noted, PINO and ZIHP time series are not included in the NIF analysis. Data from DOAR are used in the fault model, but the time series at this site stops at 2006.65 because of restrictions on access to the site.

[10] The simplest fault geometry that would fit the observations is similar to that used by *Iglesias et al.* [2004]. The plate interface is steeply dipping near the coast (fault segments 1 and 2 in Figure 1) and followed by a nearly horizontal plane (segments 3 and 4). A test of the model with more complicated geometry and a higher number of fault segments (up to 8 and extending offshore) made it impossible to resolve slip on all fault patches. Further reducing the number of faults was examined, e.g. combining fault segments 3 and 4, but it was impossible to fit the data at IGUA. Two coastal faults (Faults 1 and 2) were allowed because the data could not be fit at the coastal sites with one fault, particularly the vertical component. Recall that the transient signal is quite different at CAYA/COYU (Fault 1) and ACAP/CPDP (Fault 2). Small variations in the size and location of these faults result in models that also fit the observations, indicating the difficulty in resolving slip with limited along-strike stations. The model solves for slip in both the dip and strike direction for each fault at each epoch. The critical parameter in the NIF is the temporal smoothing parameter alpha. Various alphas were tested, trading off smoothness against fit to the observations; the models shown here used alpha = 0.01.

[11] The fit of the model to the individual station position observations can be seen in Figure 2. Recall that by removing the steady-state velocity, positions before 2006.25 should show no significant motion. Within the observational errors, this is generally observed in the time series. The common mode term in the NIF removes most of the seasonal signature often seen in GPS time series. The transient signal is fit better in the north component than in the east component, but this is consistent with the respective formal errors. The vertical model (auxiliary material Figure S1) fits the observations at most of the sites, but does not properly detect the acceleration in the vertical component at MEZC, COYU, and CAYA. Again, it is understandable that the NIF will fit the less precise vertical observations worse than the horizontal observations.

[12] Significant fault slip is observed in both the strike and dip directions (Figure 3), with the latter less well determined than slip in the strike direction. The ability to determine fault slip in the dip and strike-slip directions can be seen both in the formal errors and in how well zero slip-rate can be recovered before the transient begins. Because we are 1) using a Kalman filter to estimate fault slip, 2) the transient ended in late 2006/early 2007, depending on the site and 3) the time series for most sites ends in early February 2007, fault slip is not well resolved between November 2006-February 2007. In order to compensate for this model deficiency, artificial observations were added in June and July 2007. Station positions were computed at February 15, 2007, and then it was assumed that the stations moved with the steady-state velocity until summer. The effect of this constraint is to return the slip rate on Fault 3 closer to steady state, which is consistent with the time series which show that the transient is over.

[13] As shown in Figure 4, slip propagated along-strike most significantly on faults 1 and 4. In the dip direction, faults 3 and 4 are responsible for the largest component of slip. Independent analyses of the 2002 SSE show that fault slip was also largest downdip [*Yoshioka et al.*, 2004; *Iglesias et al.*, 2004]. This region corresponds to the transition zone. Likewise, this study of the 2006 SSE and previous studies of the 2002 SSE require slip in the region of Fault 4. With the 2006 transient, far more temporal (NW, SE motions early in the transient) and spatial complexity

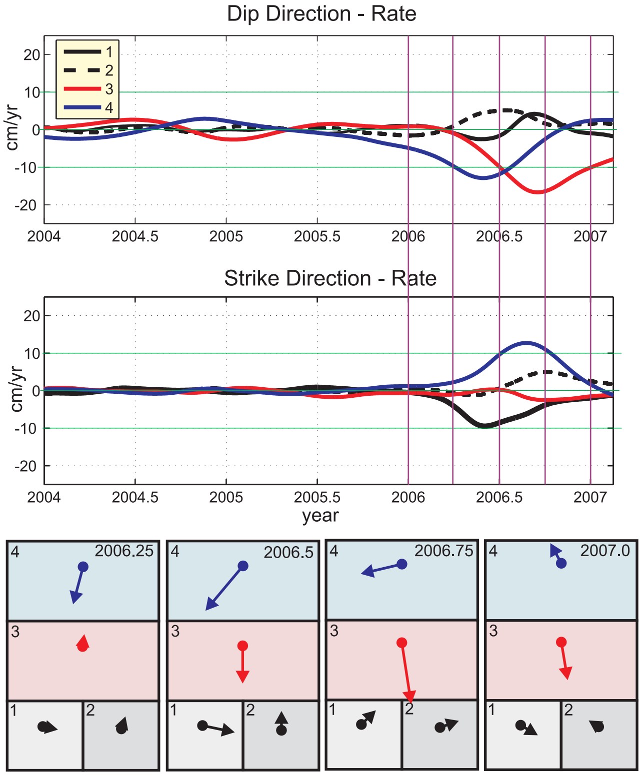

Figure 3. Fault slip rate in (top) dip direction and (middle) strike direction for the four faults defined in Figure 1. Steady-state secular deformation rates were removed from each position time series before fault slip was estimated. (bottom) Slip velocity vectors on the fault segments for different stages of the 2006 SSE.

(new observations from MEZC and greater resolution of vertical motion) can be observed because the network and constellation expanded and there are fewer data outages. A comparison of the cumulative displacements observed in 2002 and 2006 (Figure 1) confirms the qualitative similarities of the SSE's, particularly at the coastal sites CAYA and ACAP. IGUA shows significant subsidence during both events. Equivalent magnitudes are also similar for the events, ∼Mw 7.5.

[14] Although there is strong interest in calculating recurrence intervals for transient episodes, the current data do not yet allow for such an estimate. The campaign GPS record indicates there was transient slip in 1995 [*Larson et al.*, 2004], with continuous instrumentation clearly documenting large slip in 1998, 2002, 2003, and 2006. As more seismic instrumentation is deployed in Guerrero, it will be possible to examine these slip characteristics along with seismic tremor estimates. Future work will focus on evaluating how these new geodetic data can help us reevaluate seismic hazard in the Guerrero region.

5. Conclusions

[15] A large aseismic slip transient has been observed in Guerrero, Mexico in 2006. Displacement magnitudes of 6 cm over 6 months are observed along the coast and at interior sites. Available GPS stations indicate that the transient propagated from the interior to the southeast. The event was modeled using the NIF algorithm for a simple interplate geometry on four fault segments, two along the coast and two in the interior. The most significant slip in the dip direction is found on the interior faults, inland from the seismogenic zone concentrated along the coast. Noticeable along-strike slip was also estimated with a westward component for the inland fault segments and an opposite, eastward component for the coastal segments. The slip on the intermediate, inland fault segment is almost opposite to the secular interseismic deformation vector. The total slip on the coastal fault segments during the 2006 SSE suggests that some part of the elastic strain was apparently released on the seismogenic zone. The evident increase of seismicity ($M \geq 4.0$) in the most active area of the SSE (Costa Grande of Guerrero, Figure S2) favors this hypothesis. Given the size and frequency of large aseismic slip events in Guerrero, seismic hazard assessments based on steady-state deformation rates should be revised.

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