Seismic evidence of nonlinear crustal deformation during a large slow slip event in Mexico

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[1] Repeated cross-correlations of ambient seismic noise indicate a long-term seismic velocity change associated with the 2006 M7.5 slow-slip event (SSE) in the Guerrero region, Mexico. Because the SSE does not radiate seismic waves, the measured velocity change cannot be associated with the response of superficial soil layers to strong shaking as observed for regular earthquakes. The perturbation observed maximized at periods between 7 s and 17 s, which correspond to surface waves with sensitivity to the upper and middle crust. The amplitude of the relative velocity change (~10^{-3}) was much larger than the volumetric deformation (~10^{-6}) at the depths probed (~5–20 km). Moreover, the time dependence of the velocity perturbation indicated that it was related to the strain rate rather than the strain itself. This suggests that during strong slow-slip events, the deformation of the overlying crust shows significant nonlinear elastic behavior. **Citation:** Rivet, D., M. Campillo, N. M. Shapiro, V. Cruz-Atienza, M. Radiguet, N. Cotte, and V. Kostoglodov (2011), Seismic evidence of nonlinear crustal deformation during a large slow slip event in Mexico, *Geophys. Res. Lett.*, *38*, L08308, doi:10.1029/2011GL047151.

[2] Slow slip events (SSEs) recently discovered in many subduction zones are now considered as a very significant component of the strain release process and the seismic cycle because they modify the loading and releasing on the plate interface and can affect the recurrence of large thrust earthquakes. Here we present a study of the deformation that the SSEs induce in the overriding continental crust in the Guerrero segment of the Middle-America subduction zone (MASZ). In contrast to the remaining part of the MASZ, this region has not experienced large subduction thrust earthquakes for more than 100 years and, therefore, is referred as the Guerrero seismic gap [*Suarez et al.*, 1990]. At the same time, several large SSEs have been detected in Guerrero after installation of continuous GPS receivers [*Kostoglodov et al.*, 2003; *Lowry et al.*, 2001; *Vergnolle et al.*, 2010]. Those SSEs extended ≈150 km along dip, rupturing a significant part of both the dipping portion and the 35 to 40 km depth flat portion of the plate interface [*Radiguet et al.*, 2011; *Vergnolle et al.*, 2010]. While the SSEs have significant seismic moment (e.g., Mw ~7.5 for the 2006 event, according to *Larson et al.* [2007] and *Radiguet et al.* [2011]), they do not radiate seismic waves that affect superficial soft soil layers by strong shaking [*Peng and Ben-Zion*, 2006; *Rubinstein and Beroza*, 2004; *Sawazaki et al.*, 2006]. Instead, they affect the Earth materials at depths only through slow stress changes. Therefore, analyzing the response of the Earth to SSEs might provide us with useful insights for understanding the deformation mechanisms within the deeper crustal layers.

[3] We used continuous ambient seismic noise recorded by stations of the Meso-America Seismic Experiment (MASE), aligned along a North to South profile perpendicular to the coast (Figure 1), to recover the Green functions [*Shapiro and Campillo*, 2004] between pairs of stations at consecutive time intervals. The data recorded spans a 26-month period that included the 2006 Guerrero SSE (Figure 2). We computed cross-correlation functions (CCFs) between vertical components over 60-day windows that overlapped every 10 days, from January 2005 to July 2007. We repeated this computation for different period bands. The time delay between a reference correlation function (RCF) stacked over the whole period and the 60-day CCFs can be related to the velocity changes within the propagating medium [*Brenguier et al.*, 2008a, 2008b; *Hadziioannou et al.*, 2009; *Wegler and Sens-Schonfelder*, 2007]. Under the first-order assumption of a homogeneous perturbation in the crust, the relative time shift is related to the relative seismic velocity change by $\mathbf{dv/v} = -\mathbf{dt/t}$.

[4] To ensure measurements that are independent of noise source variations, we took into account the travel-time changes only within the coda of the CCFs. The coda part of CCFs is made up of diffuse waves that scattered on heterogeneities of the crust and thus tend to lose the source signature. As a consequence travel time delay measured within the coda is less sensitive to source variations. For periods between 4 s and 10 s we also measured the travel-time changes of a CCF at a given time relative to the CCF at the previous time. We thus reduced the error related to the definition of a global reference cross-correlation function, which was generally the average cross-correlation in previous studies. For periods longer than 10 s, we also defined a seasonal reference by stacking the daily CCFs of the 2005 summer season (May to September, 2005). Applying these procedures allowed the seasonal bias to be limited, and thus revealed the robust features of the temporal changes in the seismic speed (see auxiliary material for more details).[1]

[5] Global positioning system (GPS) records in Guerrero show the onset of the SSE in May 2006 [*Vergnolle et al.*,

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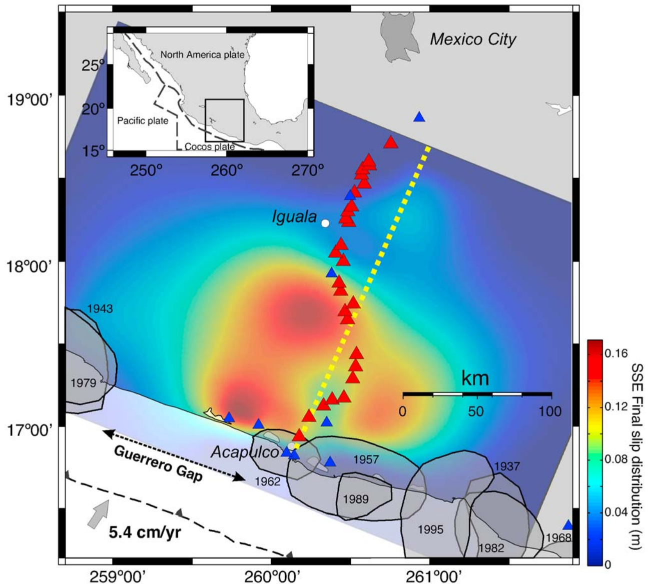

Figure 1. Map of the Guerrero region and the 2006 SSE final slip distribution on the plate interface, as obtained from the inversion of the GPS cumulative displacements (8). Red triangles, positions of the Meso-America Seismic Experiment (MASE) broad-band stations. Blue triangles, positions of the permanent GPS stations. Gray patches, rupture zones of major earthquakes that have occurred in the last century. Black dashed line, the Middle America Trench. Thick gray arrow, convergence rate between the Cocos and North America plates [*DeMets et al.*, 1994]. Yellow dashed line, position of the velocity change and dilation profiles in Figures 2b and 3.

2010]. The MEZC GPS station, which is located approximately in the middle of the MASE profile, gave a good indication of when a perturbation in the crustal elastic properties was expected (Figure 2a). Figure 2b shows the average velocity changes along the entire profile, including all of the seismic stations, for periods ranging between 11 s and 15 s, which corresponded to the Rayleigh waves essentially sensitive to the middle-crust structure. We observed a rapid decrease in the seismic velocity starting in May 2006, with a maximum value of −0.2% of the initial velocity in June 2006; this was followed by a return to the initial velocity within 2 months.

[6] We then investigated the geographical extension of the velocity perturbation by considering successive subsets of 11 neighboring stations from North to South. The result presented in Figure 2c shows that while the velocity perturbation related to the SSE affected all of the station subsets and had a North–to–South extension of at least 250 km, it was most pronounced in the northern part of the profile, rather far from the coast. We also observed the velocity change signature of the Atoyac earthquake (Mw 5.9) that occurred on April 14, 2007, a few kilometers off the Pacific coast [*Singh et al.*, 2007], which was seen as a decrease in the seismic velocity solely in the southern part of the MASE array (Figures 2c and 2d). These data demonstrate that noise-based measurements can discriminate localized speed variations and thus provide reliable information about the geographical extension of the velocity perturbation associated with the 2006 SSE. Our observations show that the SSE produced detectable changes in the elastic properties in the middle crust over a widespread area, which extended much farther inland than the slipping interface segment of the SSE (Figures 1 and 2c) [*Radiguet et al.*, 2011].

[7] To constrain the extension of the velocity perturbation at depth, we quantified the seismic velocity changes in different frequency bands, from 5.0–6.9 s to 20–27 s (Figure 3b). It has been shown both theoretically and observationally that the seismic coda is mainly composed of surface waves [*Hennino et al.*, 2001; *Margerin et al.*, 2009]. We therefore expect that the sensitivity of coda waves to velocity changes at depth depends on the period, i.e., shorter periods are sensitive to shallower structures, while longer periods sample the deeper crust. Velocity variations were measured between 1 s and 10 s during the Parkfield earthquake [*Brenguier et al.*, 2008a] and the Wenchuan earthquake [*Chen et al.*, 2010], which indicated that they could be caused by perturbations in the shallow crustal layers due to strong co-seismic shaking. Unlike the velocity changes observed following regular earthquakes, we detected no measurable changes in velocity for periods shorter than 5 s during the 2006 SSE, which suggests that the SSE did not affect the superficial crustal layers. At the same time, we observed a strong perturbation of the velocity at periods between 7 s and 20 s, which indicates that this perturbation was caused by changes in the mechanical properties at depths ranging from 5 km to 20 km. The velocity change weakens at longer periods (i.e., for larger penetration of the waves). This suggests that the increasing pressure with depth reduces the sensitivity of the elastic waves to perturbation provoked by the SSE.

[8] Our results show that recently developed noise-based passive seismic monitoring can detect perturbations of the elastic properties caused by relatively slow crustal deformation at depth. The period band in which we observed velocity changes associated with the SSE suggested a perturbation in the middle crust, rather than a localized change at the plate interface. Moreover, the perturbation of the velocity extended farther North than the SSE slipping zone at the interface (Figure 2). To better understand the nature of this observation, we computed the static strain field associated with the 2006 SSE. We used an elastic three-dimensional (3D) finite-difference code [*Olsen et al.*, 2009] with the following model settings: a 2D velocity structure below the Guerrero province [*Iglesias et al.*, 2010], the geometry of the subduction interface determined from receiver-function analysis [*Perez-Campos et al.*, 2008], and the final slip distribution of the 2006 SSE [*Radiguet et al.*, 2011]. Our numerical simulation shows that the SSE produced an extended increase in dilation in the middle crust and North of the slipping interface, with a maximum between the MEZC and IGUA GPS stations (Figure 2d). Both dilation and velocity changes affected the middle crust with similar geographical extensions, which suggested that the velocity change was related to a change in the dilation. The maximum relative change of dilation was, however, several orders of magnitude smaller than the relative velocity change observed, i.e., $\sim10^{-6}$ *versus* $\sim10^{-3}$, respectively. The strain sensitivity of the seismic velocity change $(dv/(v{*}d\varepsilon))$ is thus estimated as $\sim10^3$, which corresponds to a stress sensitivity of the velocity change of 7×10^{-3} MPa^{-1}, assuming a bulk modulus of 5×10^4 MPa. This ratio

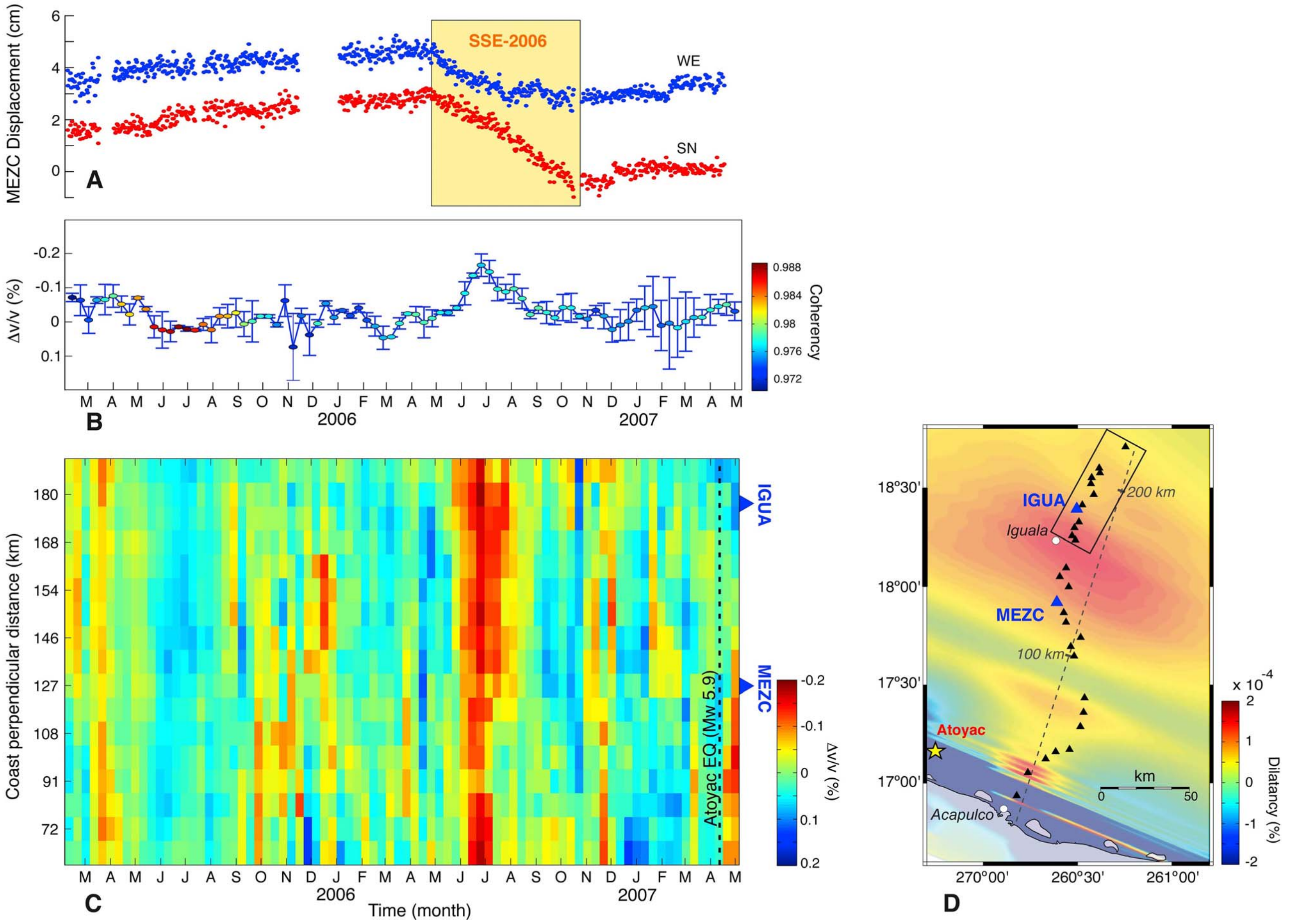

Figure 2. Correlation in time and space between the observed velocity changes and the SSE. (a) MEZC GPS station daily displacement time series for the West–East (WE) and South–North (SN) components. Yellow box, period of the 2006 slow-slip event. (b) Seismic velocity changes measured from the cross-correlation functions of the vertical-component continuous seismic records of the 26 MASE seismic stations at a period range of 11–15 s. (c) Seismic velocity changes at a period range of 11–15 s, as measured from the records of a North–to–South moving subset of 11 stations along the MASE array. Seismic velocity changes are represented as a function of the coast-perpendicular distance of the center of the subset. (d) Map of the MASE array and dilation at 15-km depth calculated from the 2006 SSE slip model. Black box, top north-moving subset of 11 MASE stations that corresponds to the first raw in Figure 2c. Gray dashed line represents the coast-perpendicular distance in km.

remains within the range estimated from active seismic experiments in regions that have been affected by transient stress changes due to tidal loading, i.e., between 5×10^{-3} and 2 MPa^{-1} [*Furumoto et al.*, 2001; *Nishimura et al.*, 2005; *Reasenberg and Aki*, 1974; *Yamamura et al.*, 2003]. Another important characteristic of the observed crustal perturbation due to the SSE is that the seismic velocity change disappeared relatively quickly after reaching its maximum (i.e., ~2 months later), as compared to the crustal strain induced by the SSE. To better assess the temporal correlation between the strain and the seismic velocity changes, we simulated the 3D quasi-static time evolution of the elastic strain field in the crust using a SSE time-dependent slip model [*Radiguet et al.*, 2011]. The results presented in Figure 3 show that the maximum velocity perturbation reached in June 2006 occurred during the phase of positive slip acceleration and was correlated with the maximum of the dilation rate.

[9] The changes in the elastic modulus (i.e., seismic velocity changes) are too large to be explained by purely linear elastic behavior, as suggested by the large discrepancy between the values of the relative velocity changes and the crustal dilation. By examining Figure 3, it can be seen that the transient velocity perturbation did not occur at the maximum of the cumulative dilation expected from the elastic model, but instead at the time of the maximum strain change. These observations suggest that a non-elastic, or at least nonlinear elastic behavior, is reached at relatively low deformation level. The onset of the velocity change, or of the non-linear regime, corresponds to dilation of the order of 10^{-6}. This also implies that the linear elastic modeling of the crustal strain associated with the SSE gives us only a rough approximation and that accounting for non-linear effects could be important for accurate quantitative description of these phenomena.

[10] While the rheology of rocks at depth is subject to debate, our data can be understood in the light of recent theoretical and experimental studies. In particular, the dynamics of the rearrangement of cracks and pores at scales smaller than wavelengths used in the measurements might

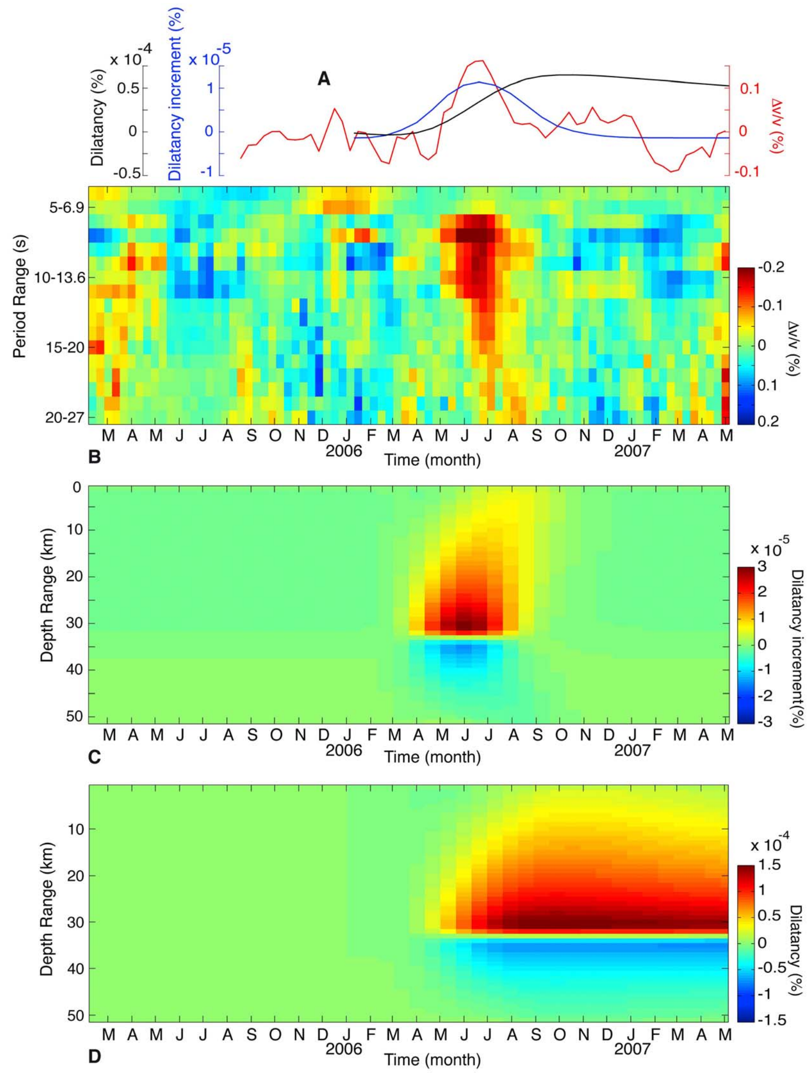

Figure 3. Comparison between the observed velocity changes computed from the entire seismic array and the modeled dilation. (a) Seismic velocity changes (red curve) measured in the period range of 10–13.6 s. Dilation (black curve) and dilation rate (increment over 20 days) (blue curve) computed at 15-km depth where the surface waves at periods of 10–13.6 s are mostly sensitive. (b) Seismic velocity changes measured at different period ranges; from 5–6.9 s to 20–27 s. (c) Increment of dilation over 20 days, and (d) total dilation, computed below the MASE array and averaged between 85 km and 220 km from the coast. Figures 3c and 3d were computed from the SSE slip-propagation model, taking into account the secular inter-seismic slip model that tended to reduce the dilation with time.

have an important role. This mechanism explains the strong decrease of elastic modulus observed in laboratory experiments on crustal samples under dynamic loading. As with our *in situ* measurements, the nonlinear elastic effects appear at strains as small as 10^{-6} [*Johnson and Sutin*, 2005; *Johnson and Jia*, 2005; *Ten Cate and Shankland*, 1996] with a strain sensitivity of velocity change of the order of 10^2. Laboratory experiments also showed that the initial and fast shear modulus reduction (i.e., seismic velocity reduction) was followed by a slower modulus recovery to its initial value, the so-called 'slow dynamics'. At the same time this recovery in the experiment is relatively fast (thousands of seconds) compared with the time resolution of our measurements, i.e., 60 days. The velocity reduction related to the SSE evolved through time very closely to the strain rate, and there was no velocity relaxation (recovery) much longer than 60 days. The confining pressure used in laboratory experiments was several orders below that expected in the middle crust. However, the nonlinear elastic effects described above may be strongly enhanced by low effective pressure. Evidence of fluid content in the crust of the Guerrero province due to metamorphic dehydration of the subducting oceanic crust indicates a possible low effective pressure due to highly pressurized fluids within the crust [*Jodicke et al.*, 2006; *Song et al.*, 2009]. Thus, the strain sensitivity of the velocity changes and the duration of the velocity recovery associated with the SSE suggest to interpret our observations in the framework of nonlinear mesoscopic elasticity, and that seismological records provide valuable insights into the deformation process at depth.

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