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A large silent earthquake in the Guerrero seismic gap, Mexico

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[1] Geodetic measurements from a network of permanent GPS stations along the Pacific coast of Mexico reveal a large "silent earthquake" along the segment of the Cocos-North American plate interface identified as the Guerrero seismic gap. The event began in October of 2001 and lasted for 6–7 months. Average slip of ~10 cm produced measurable displacements over an area of ~550 × 250 km^2. The equivalent moment magnitude of the event was $M_w \sim 7.5$. Recognition of this and previous slow event here indicate that the seismogenic portion of the plate interface is not loading steadily, as hitherto believed, but is rather partitioning the stress buildup with episodic, as opposed to steady-state or periodic, slip downdip of the seismogenic zone. This process increases the stress at the base of the seismogenic zone, bringing it closer to failure. These results call for a reassessment of the seismic potential of Guerrero and other seismic gaps in Mexico. *INDEX TERMS:* 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 1242 Geodesy and Gravity: Seismic deformations (7205); 7230 Seismology: Seismicity and seismotectonics; 8150 Tectonophysics: Plate boundary—general (3040); 8168 Tectonophysics: Stresses—general; *KEYWORDS:* Subduction, Slow aseismic transient, Seismic gap. **Citation:** Kostoglodov, V., S. K. Singh, J. A. Santiago, S. I. Franco, K. M. Larson, A. R. Lowry, and R. Bilham, A large silent earthquake in the Guerrero seismic gap, Mexico, *Geophys. Res. Lett.*, *30*(15), 1807, doi:10.1029/2003GL017219, 2003.

1. Introduction

[2] In the past few years, accurate geodetic measurements have revealed the widespread existence of slow aseismic slip events in various subduction zones around the world [*Hirose et al.*, 1999; *Ozawa et al.*, 2001; *Freymueller et al.*, 2001; *Dragert et al.*, 2001]. Several such events have also been observed within the Guerrero seismic gap, along the Pacific coast of Mexico, from global positioning system (GPS), precise leveling, and tide gauge records [*Lowry et al.*, 2001; *Kostoglodov et al.*, 2002]. These events, also called "silent" earthquakes, have equivalent magnitudes M_w of 6–7 and their durations vary from several days to a few years. The slow slip event of 2001–2002 in the Guerrero gap, which we report here, is unique as the largest reliably detected thus far anywhere in the world.

[3] The Guerrero seismic gap is a ~200 km segment of the Cocos-North America plate boundary between 99.2°W and 101.2°W. No large subduction thrust earthquakes have occurred in the NW part of the gap since 1911 (Figure 1). The region SE of Acapulco, to 99.2°W, has experienced only relatively small ($M_w \leq 7.1$) earthquakes since 1957. The width of the coupled, seismogenic plate interface in the Mexican subduction zone is estimated to be about 60 km [*Pardo and Suárez*, 1995]. If the entire gap were to rupture in an earthquake, it would give rise to an event of magnitude M_w = 8.1–8.4 [*Singh and Mortera*, 1991]. Such an event could be devastating to Acapulco and other cities in the state of Guerrero, as well as to Mexico City. In anticipation of the earthquake, the region has been instrumented with seismographs, accelerographs, and GPS receivers. The GPS network includes 7 permanent receivers and more than 25 campaign sites. It extends over all of coastal Guerrero (Figure 1), thus making it possible to monitor crustal deformation related to the seismic cycle of large thrust earthquakes in the gap.

[4] Steady state interseismic deformation along the Guerrero coast is produced by subduction of the oceanic Cocos plate beneath continental North America (NA). Three or more days of campaign-mode GPS measurements in November 1998 and October 2000 define the interseismic deformation [*Franco Sánchez et al.*, 2001]. The observed motion of the GPS stations, in the NA reference frame, is approximately N30°E, which is expected if some portion of the convergent Cocos-NA plate interface is locked.

2. Observations of Aseismic Slip, 2001–2002

[5] Continuous records from the permanent GPS stations provide valuable and accurate data for seismotectonic study of Guerrero. GPS phase and pseudorange data were analyzed with the GIPSY-OASIS software package [*Lichten and Border*, 1987]. IGS orbits were used in a network solution to define site coordinates in the ITRF2000 refer-

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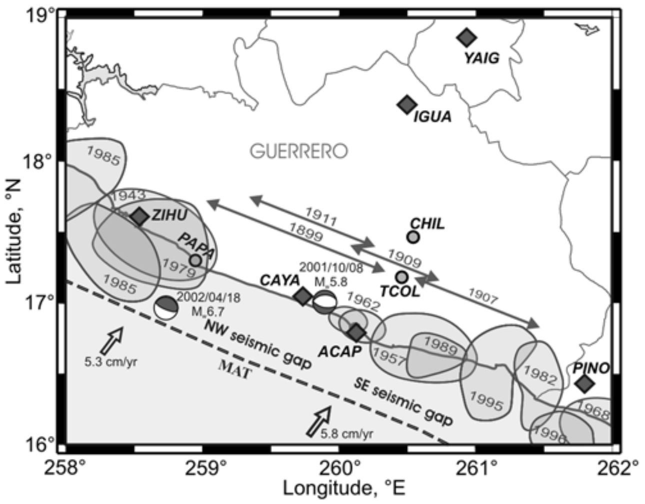

Figure 1. Seismic gap and GPS network of Guerrero. Shaded areas annotated with year are rupture zones of recent large thrust earthquakes. Double arrows, located inland, indicate the approximate rupture extent of the large earthquakes of 1899, 1907, 1909, and 1911. Open arrows indicate NUVEL1A Cocos-NA convergence velocities [*DeMets et al.*, 1994]. MAT: Middle America trench. Diamonds and circles show positions of the GPS stations (continuous and campaign measurements, respectively). Focal mechanisms of two relatively rare earthquakes, which may be causally related to the silent earthquake reported here, are also shown.

ence frame [*Beutler et al.*, 1994]. The resulting time series of north positions from seven continuous GPS sites are shown in Figure 2 (Figures with the entire time series are available in the supplementary material[1]). Prior to October 2001, stations CAYA, ACAP, IGUA, and YAIG in the central part of the gap moved northeast relative to station McDonald, Texas (MDO1) on the stable North American plate. In October–November 2001, the motion of these sites slowed. Then, near the end of December 2001, motion reversed to a relatively high velocity toward the southwest. The period of most rapid reverse motion lasted about four months (from January to April 2002). This motion is akin to an earthquake with source duration of several months, i.e., a slow or silent earthquake. Motions at stations ZIHP, PINO, and OAXA, located outside the gap, exhibit the same trend as the sites inside the gap but were delayed by about two months. Slow slip spread outward from the central part of the gap at a speed of about 6–9 km/day. A similar velocity of slip propagation was reported for a slow event along the Cascadia subduction interface [*Dragert et al.*, 2001]. Figure 3 shows that the surface deformation was observed over an area of more than $\sim 550 \times 250$ km^2.

[6] Analysis of records from the continuous GPS sites and several campaign sites permits us to estimate the anomalous displacements during the silent earthquake as well as the velocities of the steady-state interseismic phase (Figure 3). Sites PAPA, TCOL and CHIL were measured for 4–80 days beginning in May 2002, and TCOL and CHIL were also measured in November 2001. Anomalous displacement at PAPA was inferred by subtracting the interseismic steady-state displacement prior to November 2001 from the total displacement between 1998 and 2002. The maximum velocity of the recorded crustal motion during the silent earthquake, $V_{\mathrm{h}} = 14.7 \pm 1.4$ cm/yr, $Az = 202.9°$, $V_{\mathrm{z}} = 8.3 \pm 2.5$ cm/yr, occurred at CAYA, located on the coast in the central part of the NW Guerrero seismic gap. The steady, interseismic rate at this station is $V_{\mathrm{h}} = 2.33 \pm 0.04$ cm/yr, $Az = 43.8°$, $V_{\mathrm{z}} = -0.94 \pm 0.06$ cm/yr.

3. Dislocation Modeling

[7] To understand the origin of the silent earthquake, we modeled the observations in a forward sense using a 2D dislocation in an elastic half space [*Savage*, 1983]. Figure 4a compares observed and calculated displacements corresponding to one year of the steady state, interseismic phase. The plate interface includes a shallow seismogenic zone that is frictionally locked and a deeper, subhorizontal, transitional interface. Significant frictional coupling extends over a distance of 60 to 210 km from the trench. The rest of the

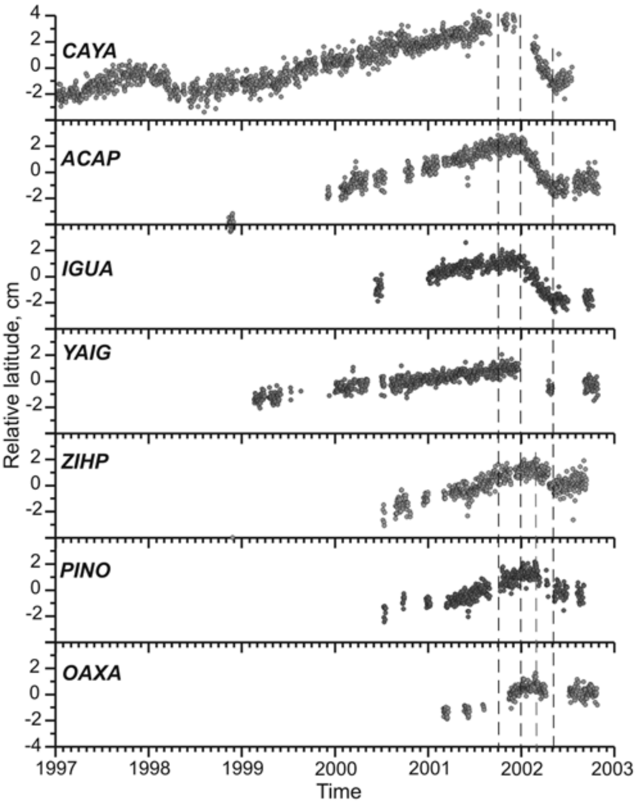

Figure 2. North (latitude) daily time series from seven permanent GPS stations recording the silent earthquake. The event is clearly visible between October 2001 and May 2002. Vertical dashed lines delimit different phases of the slow slip event. A smaller slip event is also seen on the CAYA time series during 1998 [*Lowry et al.*, 2001]. Positions are relative to McDonald, Texas (MDO1), a stable site on the North American plate.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL017219.

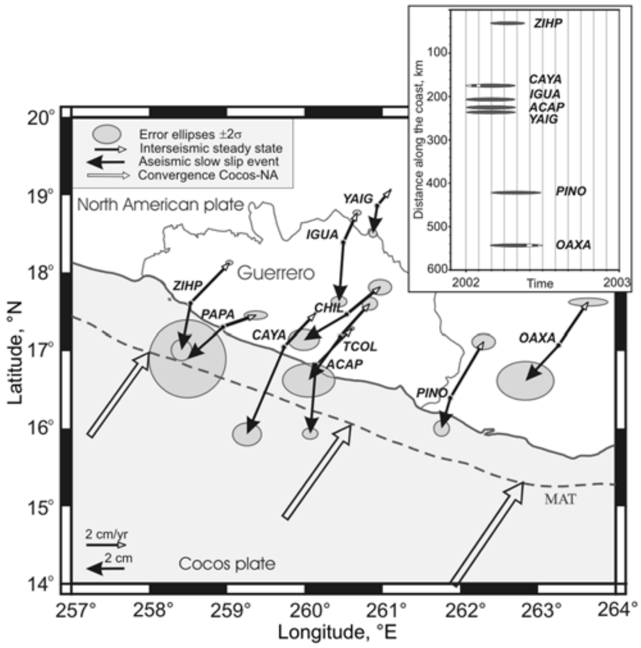

Figure 3. Velocities of GPS stations (continuous and campaign sites) during interseismic phase (open head arrows) and the displacements (with respect to MDO1) observed during the silent earthquake (solid arrows). Open arrows denote relative velocities [*DeMets et al.*, 1994] of the Cocos-NA plates. MAT: Middle American trench. Annotated points are locations of the GPS stations. Inset shows the approximate time interval of the most rapid phase of the silent earthquake at each station versus distance along coastal strike.

interface slips freely. The calculated motions agree reasonably well with the observed data.

[8] There are two end-member dislocation models that can fit the observations during the most rapid phase of the silent earthquake. The first model (Figure 4b) predicts an average reverse slip of ∼10 cm. In this model, slip occurs throughout the portion of the plate interface that was partially locked during the steady state, interseismic phase. Since slip also occurs in the shallow seismogenic zone, this model implies a diminished seismic potential for the Guerrero gap. Assuming that the average slip extended over an area of $\sim 550 \times 220$ km^2, the upper limit of moment release during the slow earthquake is about 4×10^{27} dyne-cm and the equivalent magnitude, M_w, is ∼7.7. The region of significant surface displacement is larger than the area of fault slip, so $M_w = 7.3$–7.5 may be a more plausible estimate [*Lowry et al.*, 2002].

[9] The second model (Figure 4c), which also fits the observations, requires more slip on a shorter segment of the transition interface, extending from 90 to 180 km from the trench. It leaves the upper shallow seismogenic interface locked. In this scenario, although the event would have released significant elastic strain energy accumulated previously in the subduction zone below Guerrero, seismic hazard in the Guerrero gap would not be reduced. Moreover, the slow slip on the transition interface would increase the stress on the deeper part of the locked seismogenic zone, thus advancing slightly the time of occurrence of the next large earthquake. However, in this model the stress buildup rate on the seismogenic segment may be less than if the transition zone segments were freely slipping, depending on whether the slip during the event relieved the entire slip deficit accumulated during the steady state phase. The practical importance of discriminating between the models shown in Figures 4b and 4c is obvious. A denser network of GPS stations is needed to resolve this issue.

4. Discussion

[10] We looked for anomalous seismicity in the Guerrero gap during the slow event. Two unusual, shallow earthquakes may be causally related to the slow event (Figure 1).

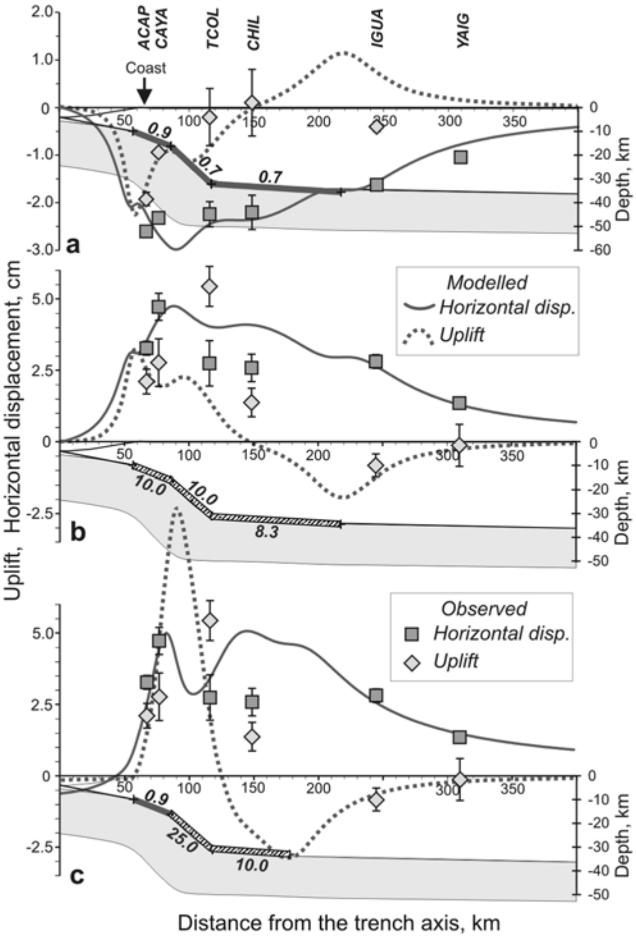

Figure 4. Dislocation models fitting the observations of (a) the interseismic steady state, and (b, c) displacement during the silent earthquake. Plate interface geometry is based on hypocentral locations and gravity modeling in *Kostoglodov et al.* [1996]. (a) The plate interface is partially locked on three segments (thick lines; bold numbers indicating the fraction of locking). The rest of the interface slips freely. (b) Aseismic slip occurs on the previously coupled segments. Hatched rectangles on the plate interface show slipping segments denoted with the slip in cm. (c) Same as (b), except that slow slip occurs over a shorter plate interface (95 km), leaving the shallow seismogenic zone (thick solid segment) partially locked. More uplift is expected near the coast in this case. Displacement errors at campaign sites TCOL, CHIL and PAPA are larger than the formal 1σ error bars shown.

On October 8, 2001 a shallow, normal-faulting, crustal earthquake ($M_w = 5.9$) occurred at Coyuca, in the central part of the NW Guerrero gap [*Pacheco et al.*, 2002]. Shallow upper plate events are extremely rare along the Pacific coast of Mexico. This event may have been triggered by the initiation of the silent earthquake. For the slow slip to trigger the normal-faulting Coyuca earthquake, the silent earthquake would have to nucleate offshore. It is also possible that the Coyuca event acted as a trigger to the slow slip. The Coyuca earthquake produced an anomalously large number of aftershocks (>300), many with normal-faulting mechanisms [*Pacheco et al.*, 2002]. The intense aftershock activity lasted 6 months, overlapping the duration of the silent earthquake. Apparently the slip event favored occurrence of the aftershock sequence. The other earthquake, on April 18, 2002 ($M_w = 6.7$), was a tsunamigenic event located near the trench [*Iglesias et al.*, 2003]. This earthquake may have been triggered by the slow event.

[11] We speculate that the shallow subhorizontal dip of the plate interface in Guerrero may be a controlling factor for the physical conditions favorable for such extensive slow slip. The 1998 slow event [*Lowry et al.*, 2001] activated a much smaller portion of the coupled thrust, and the associated seismicity was fairly low. This suggests that the "repeating transient slip" model proposed for the Cascadia subduction zone [*Miller et al.*, 2002] is not relevant to Guerrero, and perhaps the slip mode here can be quite variable from one slow aseismic event to the next. Silent earthquakes in Guerrero in 1972, 1979 [*Kostoglodov et al.*, 2002], 1998 [*Lowry et al.*, 2001], and the discovery of the most recent in 2001–2002 call for a reassessment of the seismic potential and careful geodetic and seismotectonic monitoring of the seismic gaps in Mexico.

[12] **Acknowledgments.** We thank Wallis Hutton for helpful discussions. GPS continuous data are archived at UNAVCO (CAYA) and at SOPAC (YAIG). Yehuda Bock inspired the installation of the GPS station at Yautepec (YAIG) and provided the equipment. This research was supported by CONACYT grants G25842-T, 37293-T, PAPIIT grant IN104801, and NSF grants EAR 9725712 and 0125618. The paper was improved by suggestions of an anonymous referee. Precise orbits from the International GPS Service and Jet Propulsion Laboratory are gratefully acknowledged. Some of the figures were generated using the Generic Mapping Tools package [*Wessel and Smith*, 1998].

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