GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L07305, doi:10.1029/2007GL032877, 2008

Nonvolcanic tremor observed in the Mexican subduction zone

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Received 4 December 2007; revised 17 February 2008; accepted 28 February 2008; published 4 April 2008.

[1] Nonvolcanic tremor (NVT) activity is revealed as episodes of higher spectral amplitude at 1–8 Hz in daily spectrograms from the continuous seismological records in Guerrero, Mexico. The analyzed data cover a period of 2001–2007 when in 2001–2002 a large slow slip event (SSE) had occurred in the Guerrero-Oaxaca region, and then a new large SSE occurred in 2006. The tremor burst is dominated by S-waves. More than 100 strong NVT bursts were recorded in the narrow band of $\sim$40 $\times$ 150 km^2 to the south of Iguala City and parallel to the coastline. Depths of NVT hypocenters are mostly scattered in the continental crust between 5 and 40 km depth. Tremor activity is higher during the 2001–2002 and 2006 SSE compared with that for the "quiet" period of 2003–2005. While resistivity pattern in Guerrero does not correlate directly with the NVT distribution, gravity and magnetic anomaly modeling favors a hypothesis that the NVT is apparently related to the dehydration and serpentinization processes.
Citation: Payero, J. S., V. Kostoglodov, N. Shapiro, T. Mikumo, A. Iglesias, X. Pérez-Campos, and R. W. Clayton (2008), Nonvolcanic tremor observed in the Mexican subduction zone, *Geophys. Res. Lett.*, *35*, L07305, doi:10.1029/2007GL032877.

1. Introduction

[2] Nonvolcanic tremor (NVT) or low frequency ($\sim$1–10 Hz) tremor activity was observed recently on some subduction zone thrust faults: Japan [*Obara*, 2002; *Katsumata and Kamaya*, 2003], Cascadia [*Rogers and Dragert*, 2003], Alaska/Aleutian [*Peterson et al.*, 2007], Costa Rica [*Brown et al.*, 2005]. There are a number of studies which associate NVT and aseismic slow slip events (SSE) as a manifestation of the same process on the transition zone between the seismogenic coupled and deep free-slipping segments of the subduction interface [*Rogers and Dragert*, 2003; *Obara et al.*, 2004; *Obara and Hirose*, 2006].

[3] A straightforward technique to locate NVT uses cross-correlation functions of the waveform envelopes obtained from the continuous seismic records [*Obara*, 2002]. Unfortunately this method is not sufficiently accurate for sparse seismic networks [*Kao et al.*, 2007], particularly for the tremor source depth. A challenge to improve the accuracy of tremor localization [*Kao et al.*, 2006; *Shelly et al.*, 2006] and to uncover NVT origin resulted in a detection of low-frequency earthquakes (LFE) and very-low-frequency (VLF) earthquakes [*Ito et al.*, 2007] occurring on the plate interface, respectively downdip and updip from the seismogenic zone. The sources of VLF earthquakes and especially of LFEs were determined in the Nankai subduction zone, southwest Japan with a high spatial and temporal resolution, which revealed that the VLF earthquakes and LFEs coincide with the episodes of deep low-frequency tremors and slow slip events. Furthermore, *Shelly et al.* [2007] found that NVT in Shikoku, Japan could be just a swarm of LFEs or the effect of a series of small shear slip events on the plate interface.

[4] Discovery of NVT in other fault systems in different geodynamic environments, including the San Andreas Fault [*Nadeau and Dolenc*, 2005], may help researchers to understand its source and its relationship to the SSEs and the seismic cycle. A search for NVT in the Central Mexico subduction zone is particularly interesting in this sense because of frequently occurring large SSEs [*Larson et al.*, 2007] and the unusually wide, subhorizontal transitional plate interface. Furthermore, an absence of large subduction thrust earthquakes in the Guerrero gap (Figure 1) for the last hundred years suggests that this gap may rupture in a Mw$\sim$8 seismic event. Thus a verification of the hypothesis that one of the SSE-NVT episodes could trigger a large subduction thrust earthquake [*Rogers and Dragert*, 2003] is crucial for Mexico.

[5] In addition to a fairly good continuous GPS records along the Guerrero transect, this subduction zone segment was explored extensively with the dense MASE profile of broad band seismic stations in 2005–2007 [*Clayton et al.*, 2007] (Figure 1). A previous magnetotelluric study along the same profile [*Jödicke et al.*, 2006] may provide some constraints on the fluid dehydration from the subducting plate which is thought to be a source process for the NVT [e.g., *McCausland et al.*, 2005].

2. Data and NVT Processing

[6] First evidence of NVT in Guerrero, Mexico has come out from an analysis of continuous (20 Hz sampling) broadband records of the Servicio Sismológico Nacional (SSN) since 2001. Daily spectrograms from PLIG and CAIG stations (Figure 1) sometimes show clear synchronous episodes of higher spectral amplitude in a range of 1–8 Hz lasting from several minutes up to several hours (Figure S1).[1] Band-passed (1–8 Hz) signals corresponding

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL032877.

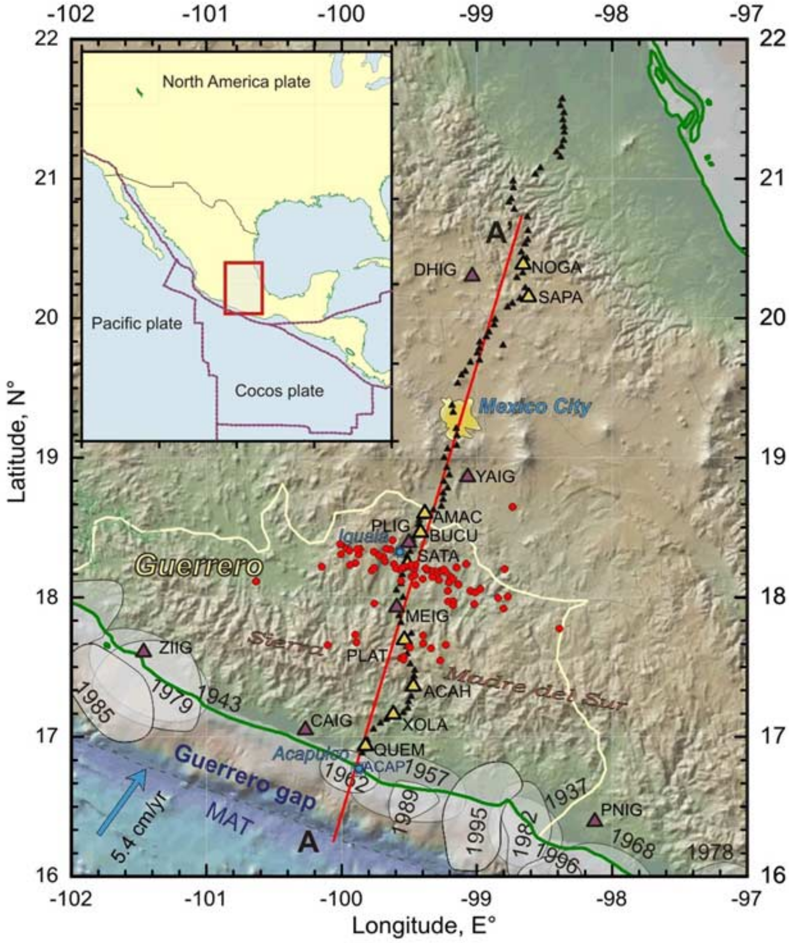

Figure 1. (inset) Location of the study area and plate boundaries. Seismotectonic setting, seismic network configuration and NVT locations. White (red) circles are epicenters of NVT bursts estimated from the analysis of MASE data (small black triangles indicate the positions of broad band seismic stations). Large dark (purple) triangles show locations of the SSN broad band stations. Large light (yellow) triangles denote the MASE stations for which the records are shown in Figure 2a. Line A-A′ denotes a location of profile presented in Figure 2b. Shaded areas along the coastline annotated with the years are approximate rupture areas of the most recent major thrust earthquakes (M $\geq$ 6.5) in the Guerrero segment of the Mexican subduction zone [*Kostoglodov and Pacheco*, 1999]. MAT is the Middle American trench. Arrow indicates NUVEL1-A relative Cocos-North America plate motion vector [*DeMets et al.*, 1994].

to those episodes is very similar to that of NVT observed in Cascadia [*Rogers and Dragert*, 2003]. The tremor signal at CAIG, located close to the Pacific coast, is noticeably weaker than at PLIG, a far inland station, and it is stronger for the horizontal components. It is impossible, however, to localize tremors in 2001–2005 because of a lack of continuous records from other SSN stations. In spite of this a visual examination of daily spectrograms from PLIG and CAIG allowed us to identify the strongest tremor bursts and compile a rough catalog of NVT activity (hours of tremor per day) in Guerrero for this epoch.

[7] Deployment of 100 three-component broadband stations in 2005–2007 during the Meso-American Subduction Experiment (MASE) provided an unprecedented amount of continuous seismic data (100 Hz sampling) along the Acapulco-Tampico transects [*Clayton et al.*, 2007] (Figure 1). The average distance between MASE stations was 5 km, so that the NVT bursts could be reliably traced at 25–30 sites (Figure 2). Rapid visual examination of daily spectrograms at a few low-noise MASE stations separated by 30–150 km (see Figure 2b for the station locations) provides a rough estimate of tremor periods. After applying a 1–8 Hz band-pass filter, the NVT are clearly evident on all 3-components at many MASE sites, with the strongest amplitudes in the horizontal plane. Particle motion patterns on stations close to and above the tremor source show that the S-wave dominates the NVT bursts (Figure S3).

[8] For the NVT locations we used waveform envelope technique [*Obara*, 2002; *McCausland et al.*, 2005]. The EW component of the record at each station is band-passed by applying Butterworth filter in the range of 1–2 Hz where the NVT/noise amplitude ratio is the highest (Figure S2). Then smoothed envelopes of these signals (Figure 2a) were processed to obtain cross-correlation functions between one reference and every other station. The time of the maximum of the cross-correlation function is regarded as the arrival time of S wave at the particular station. Finally the hypocenters are estimated using HYPOINVERSE-2000

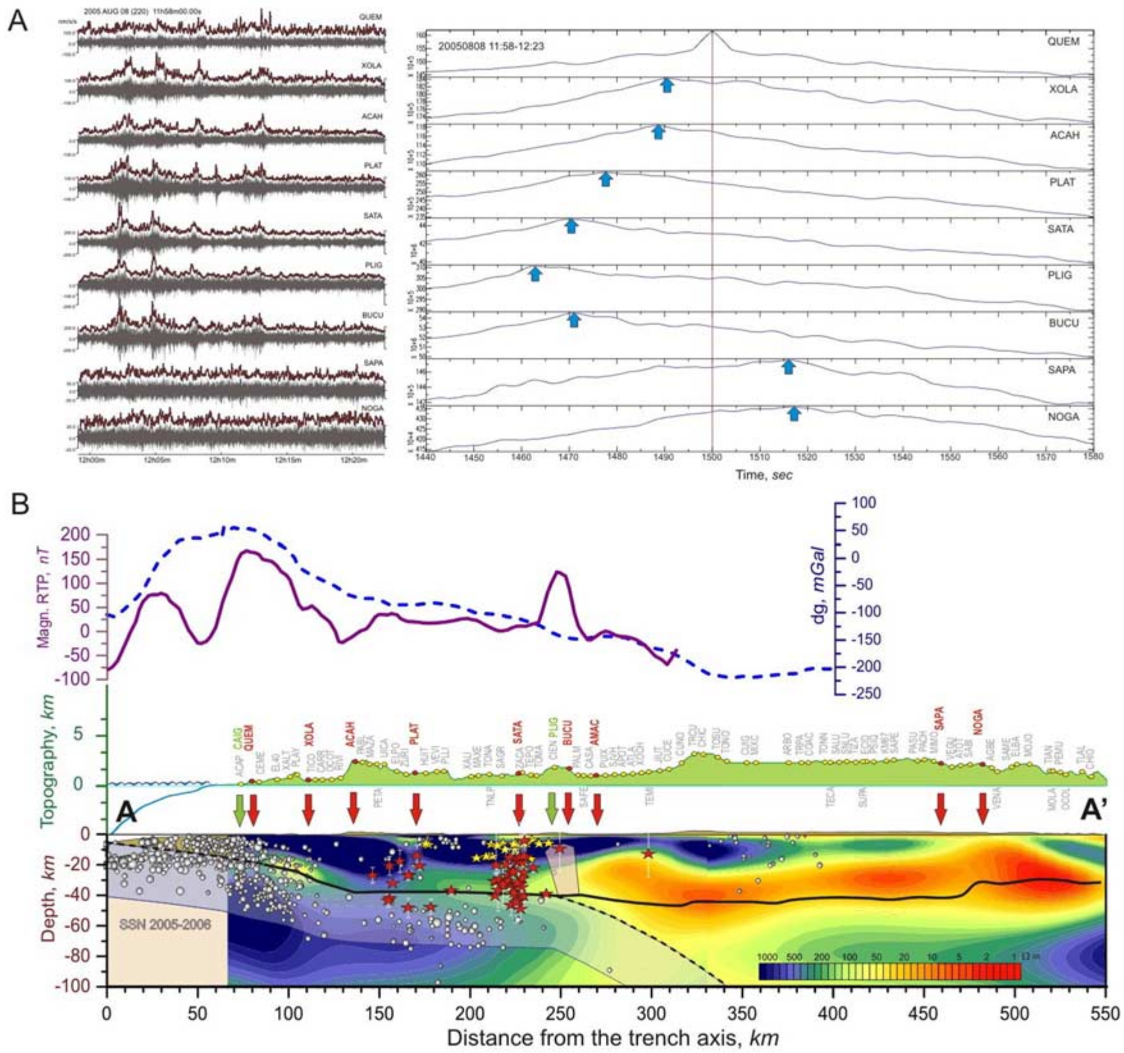

Figure 2. (a) The 1–2 Hz band-passed EW component and its smoothed envelope of the continuous seismic records at several broadband MASE and SSN stations (Figure 2b shows locations of these stations) for the time interval of ~25 min during the August 25, 2005, 11h58m NVT burst and the corresponding cross-correlation functions (CCF). A conditional reference station is QUEM. Arrows indicate a time of maximum of the CCFs at each station picked as the S wave arrival time. (b) A-A′ transect (Figure 1) that shows locations of MASE and SSN stations on the topography profile. Arrows point out the sites for which the NVT signal is presented in plate A. Solid and dashed lines in the bottom graph illustrate the Cocos-North America tectonic plates interface and Moho [*Clayton et al.*, 2007]. Red and yellow stars are the NVT hypocenters projected on the A-A′ vertical cross-section plane (yellow stars denote poorer estimated NVT with the depth errors more than 30 km). White circles are the projection of the earthquake (M > 4) hypocenters from the SSN catalog for 2005–2006 epoch. Shaded polygon area located in the continental crust, above the tip of the mantle wedge (~250 km from the trench) stands for a probable mega-intrusion of lower density and high magnetization which can explain the gravity and magnetic anomalies shown in the upper chart. Background image is a resistivity model [*Jödicke et al.*, 2006] (digital image is a courtesy of A. Jording).

[*Klein*, 2007]. The seismic velocity model used to locate the tremor is the latest 3-D tomography inversion for the Guerrero region [*Domínguez et al.*, 2006], where *V*s varies from 3.2 to 4.7 km/s in the continental crust and from 4.0 to 4.2 km/s in the oceanic crust.

[9] The NVT records from 15–25 MASE stations provide the epicenter estimates with horizontal location errors (ERH) in the best case less than 10 km but with poorer constrained depths (see auxiliary material for NVT errors' estimates), especially for those shallower than 20 km (yellow stars in Figure 2b). Apparent NVT location outliers typically come out when the analyzed seismic signal is composed from a few spatially separated concurrent NVT bursts. An implementation of mini-arrays and seismic triangulation approach [*Métaxian et al.*, 2002] may help to resolve this problem.

3. NVT Distribution and Correlations

[10] Most of the tremor epicenters recorded during the MASE deployment in 2005–2007 concentrate into a narrow band of ~40 × 150 km^2, south from Iguala City, ~18°N

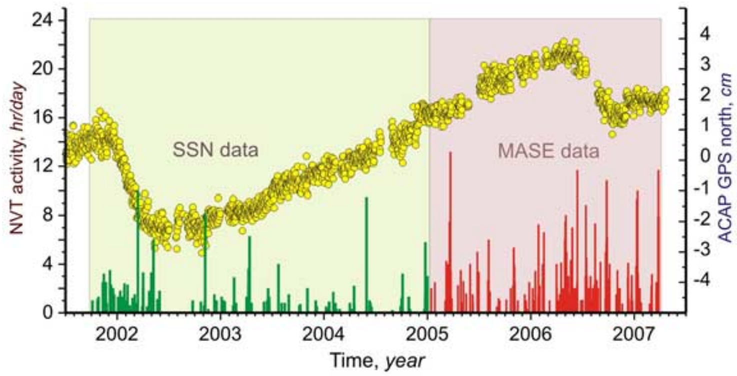

Figure 3. NVT activity (hours of tremor bursts per day) in Guerrero estimated visually from the spectrograms as a correlated 1–8 Hz higher spectral amplitude signal at PLIG and CAIG SSN stations for 2001–2005, and at several MASE stations for 2005–2007. Daily variation of latitude position of the Acapulco continuous GPS, small circles, detects two asesimic slow slip events (SSE) in 2001–2002 and 2006 as a southward motion of the ACAP station during several months, which is reverse to the long lasting secular motion between 2003 and 2006. NVT activity is relatively higher for the SSE epochs.

and parallel to the coastline. The linear distribution of the MASE stations and a poor transversal coverage of the SSN seismic stations inhibit recording possible NVT episodes beyond this area in the lateral direction. A small group of NVT bursts is localized further to the south, ~17.5°N, on the northern flank of the Sierra Madre del Sur mountain ridge. The majority of NVT bursts occur far away from the trench (~220 km) and seismogenic coupled plate interface (~120 km) located below the coast (see rupture zones of large thrust earthquakes in Figure 1). Tremor depths vary from 5 to ~50 km with the maximum number of the events occurring in the continental crust (Figure 2b). This NVT distribution is very similar to the NVT in Cascadia [*McCausland et al.*, 2005; *Kao et al.*, 2006].

[11] Local seismicity distribution (M > 4) in Guerrero for the period of 2005–2006 (SSN catalog) is anti-correlated with the NVT pattern (Figure 2b). The two groups of NVT occur at the extreme ends of the intraplate seismicity cluster. In addition, the NVT bursts do not correlate with the locations of shallow crustal seismicity. The same was observed in Cascadia: local earthquakes are absent where NVT are occurring [*Kao et al.*, 2006]. If the intraplate seismicity and NVT are both related to the dehydration of the subducting oceanic plate then a spatial correlation would be expected between these two seismic phenomena.

[12] A prevalent hypothesis explaining NVT is based on the fluid presence or its infiltration into the plate interface and overlying crust. NVT distribution in Guerrero does not support the models of long-time fluid existence as a tremor source. The resistivity profile A-A′ (Figure 2b) obtained from the magnetotelluric study [*Jödicke et al.*, 2006] clearly shows that the NVT clusters are not related to the zones of high conductivity which may be caused by the presence of fluids or partial melts.

[13] While it was not possible to locate the tremors from 2001–2005, we were able to estimate the number and duration of NVT events occurred in Guerrero between 2001 and 2007. This gives us the chance to analyze a bulk NVT activity in relation with the aseismic slow slip events [*Kostoglodov et al.*, 2003; *Larson et al.*, 2007]. Figure 3 shows the NVT activity estimated visually from the spectrograms at PLIG and CAIG SSN stations for 2001–2005, and at several MASE stations for 2005–2007. The visual analysis reveals nearly similar periods of NVT activity compared with the method of "energy" (Figure S4) in which a 1–2 Hz band-passed seismic record is filtered with a median filter and integrated, and then the resulting signal is smoothed to get a better estimate of duration and energy content of the NVT. Comparison of the median energy estimated at BUCU and PLAT may indicate a possible migration of tremors during the 2006 SSE. The 60-day averaged energy estimated at both stations clearly shows two peaks during the beginning and the end of the SSE, respectively. The first peak shows relatively higher amplitudes at BUCU while the second one is dominant at PLAT. This may indicate that the NVT activity was stronger in the north during the first half of the SSE and later migrated toward the south. An accurate location of all events is required, however, to accurately analyze the time-space migration of tremor bursts. The main inference coming from Figures 3 and S4 is that the most active NVT epochs match perfectly the occurrence of SSE in 2001–2002 and 2006. Nevertheless, several very strong tremor activity episodes are observed as well during the inter-SSE 2003–2005 "quiet" period, for example a one-month NVT discharge in March 2005. There are similar observations in other active faults (e.g. in Japan and the San Andreas Fault) when NVT activity has not complemented by any geodetic changes associated with the SSE. Nonetheless it is possible that geodetic measurements (GPS) still cannot resolve small deformations produced by SSE of moderate magnitude.

4. Discussion and Conclusions

[14] First observations of NVT in Mexico are restricted within the Guerrero subduction segment, where the sub-

horizontal plate interface extends for about 250 km from the trench. This convergence geometry results in smaller temperature and pressure gradients compared to other "normal" subduction zones [*Manea et al.*, 2004]. Thus the metamorphic transitions are more extended along the subducting plate, which provide an exceptional opportunity to study in detail the NVT and SSE. The tremor activity in Guerrero splits into two distinct cluster bands located mainly at 150–170 km and 210–240 km from the trench. According to the model of *Manea et al.* [2004] an important fluid infiltration into the continental crust may happen at these distances caused by the dehydration in the metamorphic transitions inside the underlying oceanic crust.

[15] NVT depths are poorly constrained for the most of shallow events (<20 km), however the majority of the tremors occur in the continental crust (5–40 km depth) and a few of them are localized on the plate interface or in the subducted plate crust. The main NVT cluster is located right to the south of the area with the strong magnetic anomalies [*North American Magnetic Anomaly Group*, 2002] and low gravity anomalies extended for some 50 km from north to south. To model these anomalies it is necessary to introduce a polygon-like body (Figure 2b) with a relatively higher magnetic susceptibility (K = 0.02–0.03 SI) and lower density ($\Delta\rho \sim 100$ kg/m^3), which may represent an igneous intrusion from the mantle wedge, which is undergoing a low-temperature metamorphic alteration. A mega-intrusion or a wide band of dikes with partially serpentinized mantle material are possible candidates for the source of these anomalies. This observation favors the serpentinization hypothesis of NVT origin proposed by [*McCausland et al.*, 2005], particularly because the tremor distribution is anti-correlated with high conductivity areas (Figure 2b). Accepting this model, it is still unclear why the NVT bursts concentrate at some distance (10–20 km) and only one side, to the south from the serpentinized intrusion body. In fact wider seismic network coverage is necessary to restrict the NVT area and to confirm that the presence of the mega-intrusion is a crucial condition for the NVT.

[16] Comparing NVT activity with SSE periods in Guerrero it is clear that these two phenomena are related but not of the same origin as it was noticed in several previous studies [e.g., *McCausland et al.*, 2005]. While some highly energetic tremor episodes do occur during the "quiet" inter-SSE periods, the long-term tremor activity is clearly modulated by SSE.

[17] There is a number of key issues to be considered in order to understand the source of the nonvolcanic tremor in Mexico: more accurate relocation of all NVT using new data and techniques; implementation of seismic mini-arrays to separate concurrent tremor events and improve the hypocenter estimates; a study of tremor migration, NVT modulation by SSE, triggering by large earthquakes, relation between local seismicity and NVT; analysis of isotopic compositions of hot spring gases (He^3/He^4) in the tremor area to verify if the aqueous fluids are generated by dehydration of the slab.

[18] **Acknowledgments.** This study is based on the MASE data and partially supported by PAPIIT IN102105, CONACYT 46064, SEP-CONACYT-ANUIES-ECOS M06-U02, and ANR-06-CEXC-005 (COHERSIS) project grants. We thank Ing. Casiano Jiménez Cruz, SSN (Mexico) for the recent seismic catalog and Kazushige Obara for some suggestions at an initial stage of this study. The authors gratefully acknowledge the assistance of the UNAM students in numerous field works during the MASE project. The MASE experiment of the Caltech Tectonics Observatory was funded by the Gordon and Betty Moore Foundation. Contribution 82 from the Caltech Tectonics Observatory.

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