Sesión Especial

G-GAP (THE GUERRERO SEISMIC GAP): NEW INSIGHTS OF THE SEISMIC CYCLE, EPISODIC ASEISMIC SLOW SLIPS AND NON VOLCANIC TREMORS, CRUSTAL STRUCTURES AND STRONG MOTION SCENARIOS

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SE11-1

THE G-GAP PROJECT (GUERRERO SEISMIC GAP) : INTRODUCTION AND OVERVIEW

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The G-GAP project aims at studying the seismic cycle in the Guerrero subduction zone. The project includes a strong collaboration between Mexican researchers from UNAM and French researchers from Université Joseph Fourier (Grenoble), Institut de Physique du Globe (Paris) and Université de Strasbourg.

A part of the project is devoted to the analysis of recently discovered slow slip events for which Guerrero is an exceptionally favorable place of study. Non-volcanic tremors are also observed and could bring new insights on the mechanical behavior of the subduction. Historical seismicity is being revisited. As part of the project, new permanent GPS stations have been installed, as well as seismic antennae complementing the already existing Mexican networks.

The other part of the project concerns the tectonics of central Mexico, with its associated seismic hazards, and a study of the important strong motion data available in the region in terms of ground motion predictive equations.

G-GAP benefits from a 4 year grant (Jan. 2009 - Jan. 2012) from the French agency ANR that makes possible the installation of the new equipment, supports students and gives opportunity of exchange for the participants. New data collected in the framework of the project are shared among participants and will be publicly open after a two-year period starting at the end of the project.

SE11-2

TWO SUCCESSIVE SLOW SLIP EVENTS EVIDENCED IN 2009–2010 BY A DENSE GPS NETWORK IN GUERRERO, MEXICO

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A large slow slip event (SSE) had been expected for the Guerrero gap for 2010. It was actually observed with an onset in July 2009. Comparison with the preceding large SSEs, which occurred in 2002 and 2006, highlights both persistent characteristics of the Guerrero SSEs (e.g. the localization of slip in the seismogenic part of the subduction interface), and also particularities of the 2009/2010 event (namely two distinct slip patches on the fault interface moving consecutively). The long GPS time series and the density of the GPS network provide evidence that the Guerrero SSEs, like classical earthquakes, have complex features. Despite having very short and relatively regular repeat times (~4 yr), Guerrero SSEs appear aperiodic. A shorter loading time before the 2009/2010 event than before the 2006 SSE seems to produce consistently reduced surface displacements for a group of stations in a core zone.

SE11-3

SLOW SLIP EVENTS AND STRAIN ACCUMULATION IN THE GUERRERO GAP, MEXICO

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GPS time series in Guerrero (Mexico) reveal the existence of large slow slip events at the boundary between the Cocos and North America plates. In this study, we examine the last three slow slip events (SSEs) that occurred in 2001/2002, 2006 and 2009/2010, and their impact on the strain accumulation along the Guerrero subduction margin. GPS displacements are inverted to retrieve the slip distribution during each SSE, and the inter-SSE coupling of the subduction interface. The three analyzed SSEs have equivalent moment magnitudes between 7.5 and 7.65, their lateral extension is variable, and they all show important slip in the Guerrero seismic gap. During the inter-SSE epochs the interplate coupling is high in the area where slow slip consequently occurs. In the Guerrero gap, the shallow portion of the plate interface, from the trench to the coast is weakly coupled. The average slip deficit accumulated in the Guerrero gap over a period of 12 years, corresponding to three cycles of SSEs is only 1/4 of the slip deficit accumulated on both sides of the gap. Moreover, the regions of large slip deficit coincide with the rupture areas of recent large earthquakes. We conclude that the slow slip events in the Guerrero gap release a significant part of the strain accumulated during the inter-SSE period, and probably increase the recurrence time of large subduction thrust earthquakes in the Guerrero gap.

SE11-4

SPECTRAL NVT DETECTION

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An algorithm is developed for NVT detection. Spectrograms aredetermined from daily seismograms. The spectrogram frequency vector iscut to 2 Hz to 10 Hz, the range where NVT is most easily seen, andthen is smoothed. A smoothed NVT master spectrum which has beenvisually selected is compared with the smoothed spectrogram todetermine the error between the master spectrum and the daily spectrumover time. The error is smoothed over time to remove regionalearthquakes and short duration ambient noise. An error threshold isused to determine when NVT is detected.

SE11-5

TEMPORAL VARIATIONS OF NON-VOLCANIC TREMOR (NVT) LOCATIONS IN THE MEXICAN SUBDUCTION ZONE: FINDING THE NVT SWEET SPOT

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Epicentral locations of non-volcanic tremors (NVT) in the Mexican subduction zone are determined from the peak of the measured energy and examined over time. From this data NVT is found to occur continuously at a distance of ~215 km from the trench, which we term the “Sweet Spot” because this region probably has the most plausible conditions (proper pressure, fluid content, temperature ~500 °C at the plate interface, and shear stress) for the NVT to always occur. High energy NVT bursts are also observed every few months, extending ~180 km to ~220 km from the trench with durations of a few weeks. During the 2006 slow slip event the duration and frequency of the NVT bursts increased and low energy bursts were observed ~150 km to ~180 km from the trench. We suggest that small, short term slow slip events (SsE) generate additional shear stress creating the high energy NVT bursts and allow NVT to occur outside of the Sweet Spot. SsE’s were triggered by the large, long term 2006 slow slip event (SSE) as evidenced by the increase in frequency and duration of the high energy NVT.

SE11-6

CAUSAL RELATIONSHIPS IN SILENT SEISMICITY OF CENTRAL MEXICO

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During the 2006 slow slip event (SSE) in Guerrero, Mexico, a seismic profile was deployed above the slipping interface. Data from this seismological network generated several observations, including the detection of an ultra-slow velocity layer confined to the uppermost part of the slab (Song et al., Science, 2009), high Poisson’s and Vp/Vs ratios within a large slab segment (Kim et al., JGR, 2010), and a transient reduction of surface waves velocity in the middle crust of about 0.2% due to the quasi-static slow-slip process (Rivet et al., GRL, 2011). Based on these observations, we have proceeded as follow.

The slip history of the 2006 Guerrero SSE (Radiguet et al., GJI, 2010) was put into a 3D viscoelastic finite difference code, approximating the pore pressure as Pp=B*Pc, where B is the Skempton coefficient (0<B<1) and Pc is the confining pressure. Solving the fluid diffusion equation in the model, we find that the silent earthquake induces a widespread decrease of effective pressure, Pe=Pc–Pp (i.e. dilation increase), above the horizontal segment of the plate interface, where the NVT activity has been localized by previous authors (Payero et al., GRL, 2008; Husker et al., submitted, 2011). Assuming a fluid seal along the plate interface as suggested in Cascadia (Audet et al., Nature, 2009), the time-dependent migration (velocity) of confined fluids in the ultra-slow layer is first upward everywhere and then reorganizes by pointing two ‘attraction’ poles (i.e. low-pressure slab segments), the first one 80-90 km and the second one around 150 km away from the coast.

We present NVT relocations obtained with a new and promising technique (Cruz-Atienza et al., in preparation, 2011). This technique is based on NVT energy-like and waveform correlation measurements in the three ground motion components. By superimposing the hypocentral relocations over the evolving Pp lithospheric cross-section, a surprisingly good correlation appears between the slab 'attraction' poles and a north-south NVT spatial segmentation, also reported in previous location catalogs. Both the secular and triggered NVT activity during the SSE are localized over widespread regions of the middle crust (~20 km depth), clearly above the plate interface (~40 km depth). The fluid 'attraction' poles are generated by stress concentrations associated with the SSE northernmost slip edge and the kink of the slipping interface where the slab becomes horizontal. Both stress concentrations induce important stain gradients along the slab top layer, which may open hydraulic windows allowing fluids to rise into the overriding plate. The transient velocity change observed during the 2006 SSE (Rivet et al., GRL, 2011) is a strong evidence of non-linear processes occurring in the middle crust, which imply a transient reduction of the bulk shear modulus (i.e. material strength) (Johnson and Jia, Nature, 2005). Such behavior, which is enhanced for low effective pressures (Pe) (i.e. where fluids are present), promotes shear failure and starts happening from deformation thresholds of about 10-6 that we show were clearly overcome during the 2006 SSE in the NVT locus above the plate interface.

SE11-7

LOCALIZACIÓN DE TREMORES NO VOLCÁNICOS

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Los Tremores No Volcá¡nicos (NVT) son episodios de actividad sí-smica relativamente profunda (~20-40 km) con las frecuencias de entre 0.5 y 15 Hz, asociada generalmente a las zonas de subducción. La mayor actividad de NVT ocurre sobre el área de transición entre el segmento de contacto interplaca sismogénico y el segmento poco acoplado y mas profundo. La dificultad de localización del NVT proviene de la ausencia de las fases emergentes claras en los registros símicos correspondientes al tremor que pueden duras de unos minutos y hasta horas. Algunos modelos proponen que los NVT están relacionados al metamorfismo a bajas temperaturas en las zonas de subducción y a la migración de fluidos dentro de la micro-porosidad que presentan las rocas en la zona de transición (e.g., Obara 2002). Los NVT en muchos casos están acompañando a los eventos asísmicos lentos (SSE).

El estudio de estos fenómenos es el objetivo principal del proyecto G-GAP, para lo cual se instalaron una red de mini-arreglos sí-smicos en el estado de Guerreo y Morelos, la mayorí-a de los sismómetros están distribuidos en una franja que va de Teloloapan Gro. al NW, hasta el pueblo Atenango del Río Gro. al SE del estado, tratando de tener una buena cobertura azimutal para poder determinar de una manera más exacta la localización y profundidad de este tipo de eventos.

Dado que el rango de frecuencias en las que los NVT se manifiesta con la amplitud dominante es entre 1 a 10 Hz, es muy difícil poder definir un tiempo de inicio para estos eventos, ya que en este rango de frecuencias generalmente hay mucho ruido sí-smico (ruido cultural y ruido meteorológico de periodo corto) por lo que hay que hacer filtrado de las señales para poder mas o menos distinguir el inicio o final de NVT.

El objetivo de este trabajo es comparar dos métodos de localización de NVT: el primero es por el análisis de la función de correlación de los envolventes entre registros en diferentes estaciones, y el segundo es usando la ventaja que proporcionan los mini-arreglos en registros de cuales es posible determinar las fases comunes entre las estaciones. La comparación de las localizaciones hechas por diferentes métodos muestra que aplicación de mini-arreglos tiene mejor resultado.

SE11-8

INDUCCIÓN TELESÍSMICA DEL TREMOR NO VOLCÁNICO (NVT) EN LA ZONA DE SUBDUCCIÓN DE GUERRERO, MÉXICO

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La zona de subducción de Guerrero, sureste de México, ha sido identificada como una zona de alta actividad de Tremores No-Volcánicos (NVT) (Payero et al., 2008, Kostoglodov et al., 2010). Desde 2005 han sido identificados y analizados cientos de tremores, con una duración de algunos minutos hasta varias horas. Los NVT tectónicos o "ambientales" ocurren normalmente sin alguna clara relación con los terremotos o eventos asísmicos lentos (SSE). Mientras los SSE de grandes magnitudes registrados con GPS en Guerrero excitan notablemente la actividad de SSE. Durante el funcionamiento de la red sísmica de los mini-arreglos, del proyecto G-GAP, han ocurrido más de un centenar de eventos telesísmicos (y regionales) importantes. Varios de ellos de magnitud Mw => 7.0, y otros de magnitud inferior, pero de buen interés por los efectos de excitación de NVT en México.

Después de la ocurrencia del gran sismo de Chile (2010) se detectó un fuerte disparo de actividad de NVT en Guerrero, lo cual permitió revisar minuciosamente las características de los tremores de la región disparados por otros sismos. Este efecto conocido para algunas otras regiones del mundo como NVT inducido, complementa los estudios de NVT para la zona de Guerrero.

Luego de analizar nueve terremotos de alta magnitud (telesismos y regionales) hemos encontrado que la incidencia de las ondas superficiales con un BAz entre (95º - 260º) respecto a la estación PLIG y otras estaciones de la red de mini-arreglos G-GAP, es probablemente un factor dominante para inducir la actividad de NVT. A parte de la relación observada anteriormente entre los tremores no-volcánicos ambientales y los eventos sísmicos lentos, este estudio ha remarcado por primera vez la excitación de NVT por ondas superficiales en México.

SE11-9

TRIGGERING OF TREMORS AND SLOW SLIP EVENT IN GUERRERO (MEXICO) BY THE 2010 MW 8.8 MAULE, CHILE, EARTHQUAKE

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In this study we investigate the triggering of seismic tremors and slip events in Guerrero (Mexico) by the great 2010 Maule earthquake (Mw 8.8) that occurred on February 27. We use data from the seismic mini-array of the French-Mexican G-GAP project, broadband data from the Servicio Sismologico Nacional of Mexico (SSN) and very broadband data from the GEOSCOPE UNM station in Mexico City. To study the slow slip events, we used 5 GPS stations located in Guerrero along a profile from Mexico City to Acapulco.

Our analysis of GPS time series shows that the 2010 Mw 8.8 Maule earthquake has possibly triggered the second subevent of the 2009-2010 SSE in Guerrero (see Walpersdorf et al, 2011 for a description of the double SSE in 2009-2010). This triggering of slow slip is accompanied by strong triggered seismic tremors. First, we observed triggered tremors occurring during the passing of S waves, Love waves and Rayleigh waves. The greatest amount of energy and duration accompanies the long-period Rayleigh waves, with smaller bursts during the S and Love waves. For the Rayleigh wave triggered tremor we observed the dispersion of Rayleigh waves in the envelopes of triggered tremors, which indicates a very strong modulation of the source by the passing surface wave. This correlation and modulation of tremor activity observed for the direct surface waves is clearly observed during a few tens of minutes and then is progressively lost with time after few hours.

At a longer time scale, we observe a temporal link between slow slip event and tremors. A temporal comparison between the GPS time series and the tremor activities shows that tiny variations in the ground displacements during the triggered SSE seem to correlate with the tremor activities. Such a correlation may indicates that NVT activities during the triggered SSE in spring 2010 are controlled by the stress perturbations produced by the variations in the slip history of the slow slip event.

This study shows that large amplitude long period waves produced by distant earthquakes can trigger slow slip and tremors in a mature subduction zone with an already perturbed medium like the Guerrero subduction zone in February 2010. Two types of tremors emerged: (1) Those directly triggered by the passing waves and (2) those triggered by the stress variations associated to the triggered SSE. This variety of phenomena and their relationship indicates a key role of the aseismic creep in the evolution of the Mexican subduction zone in response to a large teleseimic earthquake.

SE11-10

DETECTING LOW-FREQUENCY EARTHQUAKES WITHIN NON-VOLCANIC TREMOR IN GUERRERO, MEXICO

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We use the seismograms recorded by stations of the Meso-American Seismic Experiment (MASE) network to study the Non-Volcanic Tremors (NVT) occurring in the Guerrero region with a particular interest to detect Low Frequency Earthquakes (LFE). We show that the NVT records sometimes contain within them a series of smaller seismic events with a multiplet behavior. It is possible to pick an impulsive waveform within a tremor burst, referred to as the template, and find a set of similar events that make up an event family by correlating the template with available data. When stacked, this family reveals a coherent phase from a seismic event. The motions are the strongest along the horizontal components and when compared to synthetic seismograms, correlate extremely well with the S wave arrivals. Focal mechanisms of the identified template families are close to nearly horizontal inverse faulting reflecting the geometry of the subduction interface. Further precision of locations and of focal mechanisms of these LFEs are expected to help us to better understand the physics of the slow deformation in the Mexican subduction zone.

SE11-11

A NEW LOCATION TECHNIQUE FOR NON VOLCANIC TREMORS AND LOW FREQUENCY EARTHQUAKES

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Do the slab fluids inferred in the Guerrero province may migrate during successive slow slip earthquakes (SSE) into the continental crust? and, if so, which implications would be in terms of non volcanic tremor (NVT) triggering? Reliable evidence of NVT hypocentral locations above the plates interface (i.e. within the deep and intermediate continental crust) would be critical to constrain and support a given model relating the silent earthquakes phenomenology. To this end, we present NVT and low frequency earthquakes (LFE) relocations during the 2006 SSE time span with a new and promising technique (Cruz-Atienza et al., 2011). This technique is based on NVT energy-like and waveform correlation measurements in the three ground motion components. By means of a source-scanning grid search, and a large database of both synthetic seismograms and theoretical arrival times computed with ray tracing, the algorithm looks for the hypocentral locations that minimize an error function between observed and synthetic energy-like profiles, and both P- and S-waveform correlations. We test the algorithm by locating both finite-difference synthetic NVTs (Cruz-Atienza, 2010) and the whole NVT catalogue (more than 250 events) introduced by Husker et al. (G.Int., 2010) for the Guerrero province during the period of interest. Our locations first confirm the horizontal segmentation of the NVT activity during the 2006 SSE previously reported (Payero et al., 2008; Husket et al., 2011). Secondly, the NVT activity triggered during such SSE seems to be localized in the middle crust (~20 km depth), definitively above the plate interface (~40 km depth), where anomalous non-linear crustal behavior has been suggested (Rivet et al., 2011). This behavior, which promotes shear failure and is enhanced in the presence of fluids, is an attractive candidate to explain, at least partly, the NVT triggering associated with quasi-static SSE crustal deformation.

SE11-12

LOW FREQUENCY EARTHQUAKES LOCATIONS IN GUERRERO, MEXICO

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In recent years, many low#frequency earthquakes (LFEs) has been discovered worldwide. The low-frequency earthquakes or LFEs occur almost exclusively as part of a non-volcanic tremor (NVT) signal. The NVT and the LFEs are located approximately in the same region and exhibit similar behavior [Obara et al., 2002, 2004, 2006]. It is not known if the LFEs and NVT represent the same phenomena, its close association means that their mechanisms are probably linked. The non-volcanic tremors (NVT) was first time identified in the Nankai subduction zone, southwestern Japan, later observed in the Cascadia subduction zone, Alaska, Costa Rica, as well as subduction zone of Guerrero in Mexico. These non-volcanic tremors have been explained as a swarm of low-frequency earthquakes [Shelly et al., 2006, 2007]. For this reason the location of the LFEs could give us a better understanding of the area where the NVT occur in Mexico and obtain more precise locations of these phenomena. Here we presented a catalog of the LFEs in the non-volcanic tremors and their locations for the period from 2005 to 2007. To identify the LFEs we filtered the signal between 1 and 8 Hz, and we find the better events for the largest number of stations for make a better location. The data used correspond to the the broadband records of the project MASE (Middle America Subduction Experiment) stations.

SE11-13

COMPLEX RELATIONS BETWEEN SLOW SLIP EVENTS, NON-VOLCANIC TREMORS, AND SEISMIC WAVE VELOCITY CHANGES IN GUERRERO MEXICO

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Over the last 6 years an important effort has been done in geodetic and seismic instrumentation of the Guerrero subduction zone e.g. the MASE seismic experiment (from 2005 to 2007) and the GGAP project, both a seismic and a geodetic experiments (from 2009 to 2011). Analyzing these continuous geodetic and seismic recordings, we observe non-volcanic tremors (NVT) activities and seismic velocity changes during two large slow slip events (SSE) sequences in 2006 and 2009-2010. Here we propose to compare the occurrence in time and space of SSEs, NVTs, seismic velocity changes and seismicity over the two last SSEs in order to better understand the complex mechanical behavior of the subduction zone in this region.

A perturbation of the mechanical properties of rocks within the Earth's crust has been recently observed from the observation of a velocity perturbation associated with quasi-static deformation at depth produced by the 2006 SSE (Rivet et al. 2011). This velocity perturbation maximizes in the middle crust at 20km depth. Similarly we observe a velocity decrease during the 2009-2010 SSE. This last SSE presents two distinctive slipping patches (Walpersdorf et al, 2011). The velocity drop is greater at the time of the first subevent, which occurred below the seismic array, than at the time of the second subevent.

During the 2006 SSE, Kostoglodov et al. (2010) and Husker et al. (in prep)) observe an increase in NVT activity. Using the slip model that describes the slip evolution during the SSE (Radiguet et al., 2010) we observe that the NVTs follow the slip front where the shear stress maximizes. However other NVTs burst are observed outside the SSEs period and are not associated with SSEs or velocity changes. Only one of these bursts in 2005 is clearly associated to a small SSE detected on geodetic measurement and a velocity drop. These observations suggest a rather complex relation between slow slip and NVTs activity.

Zigone et al. 2011 show that an NVTs sequence and the second subevent of the 2009-2010 SSE were triggered by the 2010 Maule earthquake (Mw 8.8). We investigate the relation of other large teleseismic earthquakes with NVTs and SSEs from 2005 to 2011. No other large teleseismic event triggered NVT or slip. This suggests that the dynamic triggering of NVTs and slip is dependent of the state of stress of the subduction interface.

The relation between the seismic velocity perturbation and the strain due to the SSEs suggests that the deformation of the overlying crust shows significant nonlinear elastic behavior. NVTs could be as well produced by the deformation and related to this nonlinear elastic behavior of the overlying crust. However precise location of NVTs at depth is needed to be conclusive about the relation between velocity changes and NVTs.

SE11-14

CRUSTAL TRAVEL-TIME TOMOGRAPHY BELOW SOUTHERN MEXICO

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P and S wave travel-time tomographies as well as a Vp/Vs ratio image of the crust below southern Mexico were developed using data from the MesoAmerican Subduction Experiment (MASE) broad band temporary network. A 2-D ray tracing pseudo-bending algorithm was employed and a damped least-square method to perform the inversions. The profiles have their origins at the Pacific coast and run 205 km inland perpendicular to the trench and sample the crust and the subducted Cocos slab. Results show fast velocities to the south of 40 km over the descending section of the slab, a low P-wave anomaly just where the slab bends to become subhorizontal and low velocities above the slab north of 100 km from the coast for both waves. The Vp/Vs image show two areas with high values south of 60 km where the slab descends and between 90 â€“ 140 km from the coast indicating the presence of fluids in the NVT (Non-Volcanic Tremor) zone; low values where the slab bends indicating that the zone is dominated by

stresses and normal values north of 160 km that depicts a combination of fluid presence and high temperature.

SE11-15

ANALYSIS OF GREEN FUNCTIONS OBTAINED BY CROSS CORRELATIONS FOR MASE STATIONS

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We used continuous records of broadband seismic stations of the MASE experiment to obtain observed Green´s functions using the method of ambient noise cross-correlations. The experiment consisted of 100 stations distributed along a perpendicular line to the Mesoamerican trench across the Valley of Mexico.

The stations recorded continuously at 100 sps for more than two years. The geometry of the array provide a good opportunity to study the attenuation effects along the coast-perpendicular structure.

The method we used to compute Green functions involves a strong data pre-processing (temporal normalization and spectral whitening). However, our results show that the amplitude of the cross-correlations still contains information about the surface waves attenuation and probably local amplification effects. Records from two regional earthquakes located close to Acapulco were used for comparison.

SE11-16

OBSERVATIONS OF THE HYDROACOUSTIC T PHASE FROM THE GREAT 2010 CHILEAN EARTHQUAKE USING DATA FROM G-GAP AND OTHER NETWORKS

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The French-Mexican Guerrero Seismic Gap (G-Gap) project was designed to study slow slip events and nonvolcanic tremor in a region of the Middle America Trench where no significant earthquakes have occurred in about one hundred years. It includes a total of 10 seismic mini-arrays which recorded T waves produced by the February 27, 2010 Chilean earthquake (Mw = 8.8) at distances of about 300 km from the 1000-m depth contour (the acoustic-to-seismic conversion point) along the great circle path. This is significant given that T waves are most often observed on island stations and stations very close to the shoreline, or using hydrophones. Subhorizontal subduction of the slab in Guerrero may act as a waveguide and probably explain the long distance sensitivity of inland stations to the T phase. Additionally we have used records from other continental stations provided by the Mexican Servicio Sismológico Nacional (National Seismology Bureau) as well as stations on Socorro Island in the Mexican Pacific, which the Bureau operates jointly with the Comprehensive Nuclear-Test-Ban Treaty Organization. Data were also obtained from the Global Seismographic Network (GSN) through the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC). We are currently analyzing the effect of a long source time function (and rupture propagation) on the observed T waveforms. We are also studying the polarization in order to determine the direction the wave is coming from. Lastly, we are exploring the bathymetry along the 1000-m depth contour to find the best acoustic-to-seismic conversion point.