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ATTENUATION OF GROUND MOTION PERPENDICULAR TO THE MEXICAN SUBDUCTION ZONE

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ABSTRACT

Attenuation of ground-shaking with distance and across different geological units and tectonic regions is of great importance for reliable and accurate ground-motion prediction. In this work, we investigate the differences in ground-motion attenuation across the Mexican subduction zone by comparing observational constraints with new numerical modeling results. Tejeda-Jácome and Chávez-García (2007) reported significant variation in seismic motion attenuation for two paths perpendicular to the Mexican Pacific coast: Guerrero and Colima. Their models predict stronger ground motions for hypocentral distances larger than 100 km for the northern section of the subduction zone (Colima) than for the southern section (Guerrero). We test these findings, considering two possible explanations for the observed differences: (1) differences in the subducting slab geometry between Colima and Guerrero; (2) variable shallow structure of the overriding plate due to the presence of the Trans-Mexican Volcanic Belt (TMVB) that strikes obliquely to the Middle American trench. We conduct 2D P-SV pseudo-spectral numerical simulations to investigate which of the two hypotheses better explains the observed attenuation properties. We find that the TMVB, closer to the coast in Colima area, better describes the differences in attenuation perpendicular to the Mexican subduction zone. These findings will be important for local ground-motion prediction for seismic hazard studies.

INTRODUCTION

Studies in seismic risk require ground-motion models to predict expected ground-motion at given distances for future earthquakes. Reliable networks like those in Los Angeles, USA or Tokyo, Japan, which include many permanent strong motion stations have provided useful data for this purpose. However, in developing countries with seismically active regions the situation is very different. Only few sparse strong motion networks exist or are just now being installed, and the high quality data are scarce. In Mexico, strong motion instrumentation has favored the Southern segment of the Pacific subduction zone (mainly around Guerrero), where the high seismicity rate allows obtaining useful data in a short time span. The data recorded in Guerrero has been used to derive ground motion prediction equations (GMPE) for both interplate (Ordaz et al., 1989) and for inslab, intermediate depth events (García et al., 2005). Unfortunately, due to lack of data, those prediction equations have been applied unchanged to events occurring on different sections of the subduction zone.

An additional complication in central Mexico is a phenomenon that is known as regional amplification. Singh et al. (1988) showed some differences between attenuation of ground motion along two paths; one parallel to the coast and another perpendicular to the coast. Later, Ordaz and Singh (1992) and Cárdenas et al. (1997) showed that in the frequency band from 0.3 to 1 Hz, ground motion on rock sites in central Mexico is amplified about a factor of 10 relative to sites at similar hypocentral distances along the coast.

For the region of Colima, located in the northern end of the Mexican Pacific subduction zone (Fig. 1), Tejeda-Jácome and Chávez-García (2007) presented equations for the estimation of ground motion. The seismicity rate is lower than further south, however, large earthquakes do occur in Colima, as shown by the two most recent Mexican destructive events of 1995 and 2003 ($M_w = 8$ in 1995, Pacheco et al, 1997, and an $M_w = 7.6$ in 2003, Yagi, et al., 2004, Nuñez-Cornú et al., 2004). Unfortunately, there had been no previous studies of ground motion attenuation using locally recorded data. Tejeda-Jácome and Chávez-García (2007) used seismic records obtained in Colima (along a line perpendicular to the coast), and found that larger ground motions were predicted for hypocentral distances larger than 100 km relative to the ground motion predicted using data recorded in Guerrero, in the southern section of the subduction zone. They observed differences between their results and other GMPE in terms of PGA and pseudo acceleration response spectra (PSA) for 5% damping. The most prominent differences between the GMPE developed by Tejeda-Jácome and Chávez-García (2007) and the GMPE obtained for Mexican data from Guerrero were observed for hypocentral distances larger than 100 km.

In this study we test two hypotheses to investigate the cause of the difference in the attenuation of seismic energy between Colima and Guerrero regions. We use 2D P-SV numerical modeling considering the pseudo-spectral method. The first hypothesis explains the differences as due to the different tectonic structure related to the subducting plates between Colima and Guerrero. The second one explains those differences as due to the different shallow structure in the overriding continental plate where the TMVB is located.

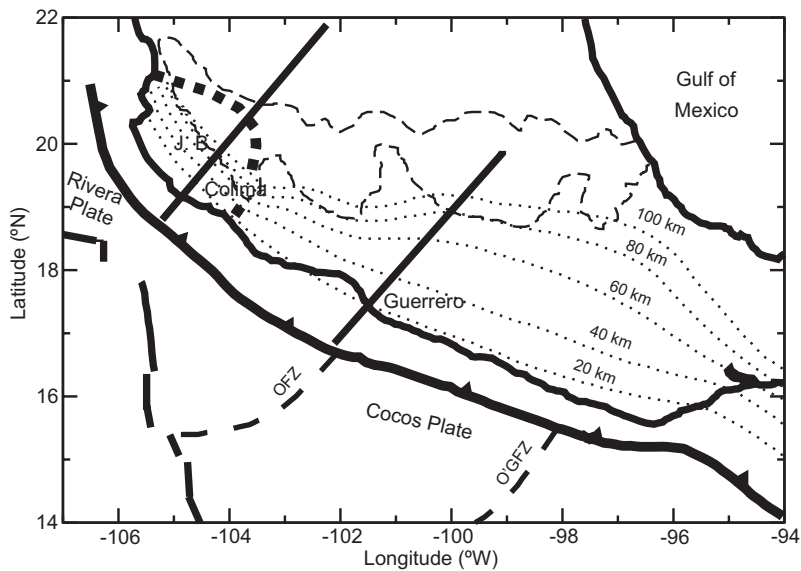


Fig. 1. Map of the main tectonic regime of southern Mexico. The thick, solid line with solid triangles shows the Middle America Trench, and the two thick, solid lines perpendicular to the coast show the locations chosen for the 2D cross-sections that were modeled. The dashed line in the continent shows the outline at the surface of the Trans-Mexican Volcanic Belt (TMVB). The thick dashed line on the western side of Mexico shows the outline of the Jalisco block (J. B.). The dotted lines show the depth contours of the subducted Cocos slab. The dashed lines in the ocean are the Orozco Fracture Zone (OFZ) and the O'Gorman Fracture Zone (O'GFZ).

THE 2D MODELS

Figure 1 shows a map of southern Mexico with its main tectonic regime. The subduction zone extends along the Pacific coast with the Cocos plate subducting below the North American plate in the southern section, while to the north, the tectonic regime becomes more complex, with the interaction between three different plates: Rivera, Cocos, and Pacific. Furthermore, the existence of a microplate

has been proposed where the Jalisco block interacts with the Rivera and the Cocos plates (DeMets and Stein, 1990; Bandy et al., 1995). The subduction zone along the Pacific coast of Mexico, divided in four sections by Pardo and Suarez (1995), has significant changes in dip, subducting rate, and geometry. A general description is given by Kostoglodov and Pacheco (1999) as shown here. To a depth of 30 km, the dip of the interplate contact geometry is constant, and lateral changes in the dip of the subducted plate appear once it is decoupled from the overriding plate. In general, subduction rate is faster to the south. In front of the Jalisco block (Fig. 1, in the north), the Rivera plate has a dip larger than 45° and subducts at a low rate of 1.4 cm/yr. The Cocos plate below Colima shows a similar dip to that of the Rivera plate but subducts at a faster rate (4.7 cm/yr). To the south, the dip of Cocos plate becomes shallower and is almost subhorizontal at Guerrero (where it subducts with a velocity of 5.9 cm/yr), before increasing again further south to more than 45° in Chiapas (just to the right, outside of Fig. 1). These variations along the subduction zone are the first possibility to explain the differences in attenuation of ground motion perpendicular to the coast between Colima and Guerrero. A second possibility is the Trans-Mexican Volcanic Belt (TMVB) associated with the subduction zone. This large structure of about 1,000 km long and between 80 and 230 km wide makes an angle of approximately 16° relative to the Middle American Trench. Pardo and Suarez (1995) explain this angle by the lateral variation in the subduction parameters and geometry.

Figure 2 shows the 2D models tested in this study. The model for Guerrero reproduces that of Furumura and Singh (2002). This model was derived from refraction and gravimetry studies (Valdes et al. 1986 and Valdes and Meyer, 1996). It includes the upper-mantle structure, a three layer crust and the subducting Cocos plate with a dip angle of about 10° and a thickness of 30 km. The TMVB is represented by a thin (2 km) surficial layer. In this model we include topography, which is significant only for epicentral distances larger than 300 km.

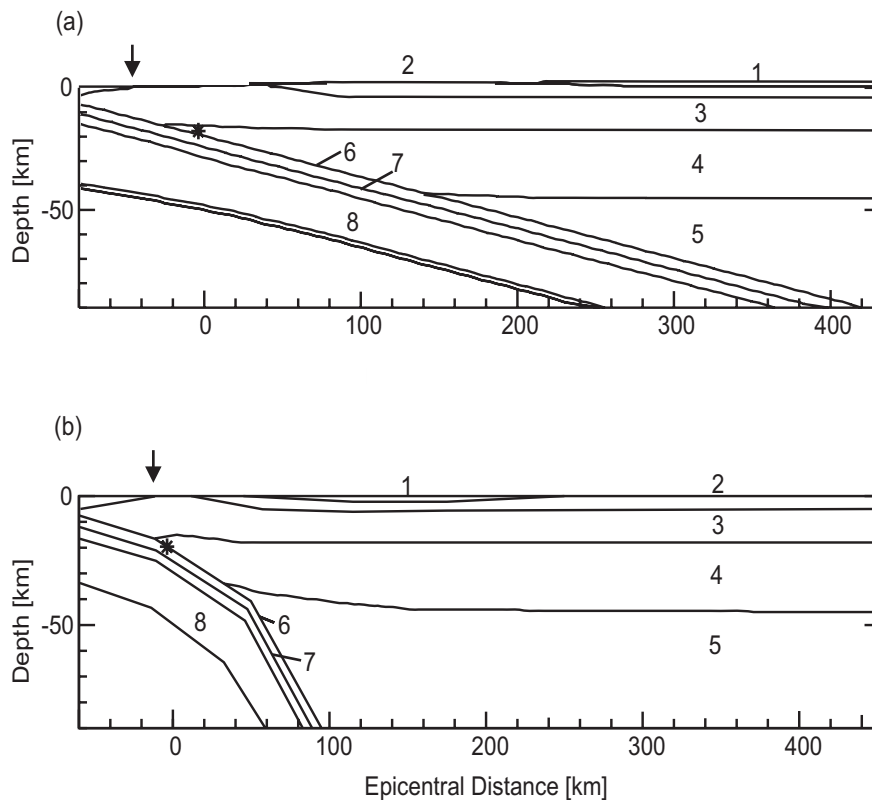


Fig. 2. (a) 2D model for the Guerrero cross-section (after Furumura and Singh, 2002). (b) 2D model for the Colima cross-section (after Bandy et al., 1999). The numbers indicate the layer whose properties are given in Table 1. The star indicates the location of the source. The arrow on the top of each model indicates the ocean/land transition.

The 2D model chosen for Colima was built from Bandy et al. (1999) and Kostoglodov and Pacheco (1999). It is based on gravity and seismicity studies. The model is similar to that of Guerrero, except for the dipping angle of the subducting plate which, at a depth of about 40 km, increases to about 45° . As can be seen clearly, the TMVB is in a different location, only 50 km from the coast. In table 1 we show the mechanical properties of the different layers, where numbers in square brackets refer to layers in Fig. 2. We conducted two simulations for each of the two sections: in the first case we did not include the TMVB, and in the second one, we included a thin

layer that represents this structure. The velocities for the TMVB are based on measurements by Gomberg et al. (1988ab) and Alesina et al. (1996) and were correlated with density measurements by Molina-Garza and Urrutia-Fucugauchi (1994).

We used a 2D version of the Fourier spectral method (Kosloff and Baysal, 1982; Kosloff et al., 1984; Furumura and Takenaka, 1996) in our simulations. The two discretized sections have the same dimensions: 512 km in length and 128 km in depth, and with a uniform grid spacing of 0.25 km, the grid have 2048 by 512 nodes. In order to attenuate artificial reflections at the boundaries, we used a 20 node buffer zone (Cerjan et al., 1985). By the careful analysis of the receivers close to the boundary we found that this boundary condition did not generate artificial reflections in our models. In addition, we repeated the computation using a larger grid size and obtained the same result. Computations are accurate up to 4.0 Hz given the minimum velocities in our models.

In our simulations we used a line source, perpendicular to the model, with a thrust faulting mechanism. The source was located at coordinates 104.4 °W, 18.7 °N and at a depth of 17 km. Epicentral distance is referenced to the location of the source. The source time function was given by a pseudodelta function (Herrmann, 1979) with a duration of 0.25 s. We computed synthetic seismograms for 201 receivers (separated 2 km) on the surface, with a total duration of 150 s.

Table 1. Model Parameters used in the 2-D simulation. The numbers in square brackets refer to Fig. 2.

	Vp (km/s)	Vs (km/s)	ρ (t/m ³)	Qs	Thickness* (km)
Layer 1 (TMVB) [1]	4.0	2.0	2.0	150	2.0
Layer 2 [2]	5.2-5.3	3.0-3.1	2.3	200	6.0
Upper crust [3]	5.5-5.8	3.2-3.4	2.8	400	18.0
Lower crust [4]	6.4-7.1	3.7-4.1	2.9	600	27.0
Upper mantle [5]	8.2-8.4	4.7-4.8	3.3	800	—
Oceanic crust [6]	5.0-7.0	2.8-3.9	2.1-3.5	150	4.0
Oceanic basalt [7]	6.8-7.1	3.8-3.9	2.9	200	4.0
Oceanic mantle [8]	8.2-8.6	4.7-4.9	3.32	1000	16.0

RESULTS

We present in detail only the results for the Colima section because those for the Guerrero were presented in Furumura and Singh (2002). Figure 3 shows the reduced travel time synthetic seismograms (travel times less the corresponding epicentral distance divided by a velocity of 8.0 km/s) of the radial component ground velocity. We lowpass filtered the traces with a 4.0 Hz two-pole causal Butterworth cutoff. These results correspond to the model without the TMVB. The predominant pulses observed in this figure are the direct P and S phases (for epicentral distances smaller than 100 km), and PmP phases, guided by the crustal structure (around 12 s time, between 100 and 250 km).

In Fig. 4 we show the comparison between attenuation in Colima and Guerrero as a function of epicentral distance. In this case we do not include the TMVB. The Fourier amplitude of the S-wave window of the simulated traces was smoothed using an octave band filter. Figure 4 shows the value of the smoothed amplitude spectrum at 0.5 Hz, normalized by its value at 50 km epicentral distance. We observe that attenuation is very similar between the two models, which shows that the different geometry of the subduction zone has a small impact on observed ground motions. Localized bumps in the curve for the Guerrero model around 100 and 240 km are wide angle SmS reflections (Furumura and Singh, 2002). The differences in relative amplitude are smaller than a factor 2 and appear only in small epicentral distance windows. We obtained very similar results when we plotted PGV as a function of distance for our synthetics (which include the frequency band 0 to 4 Hz).

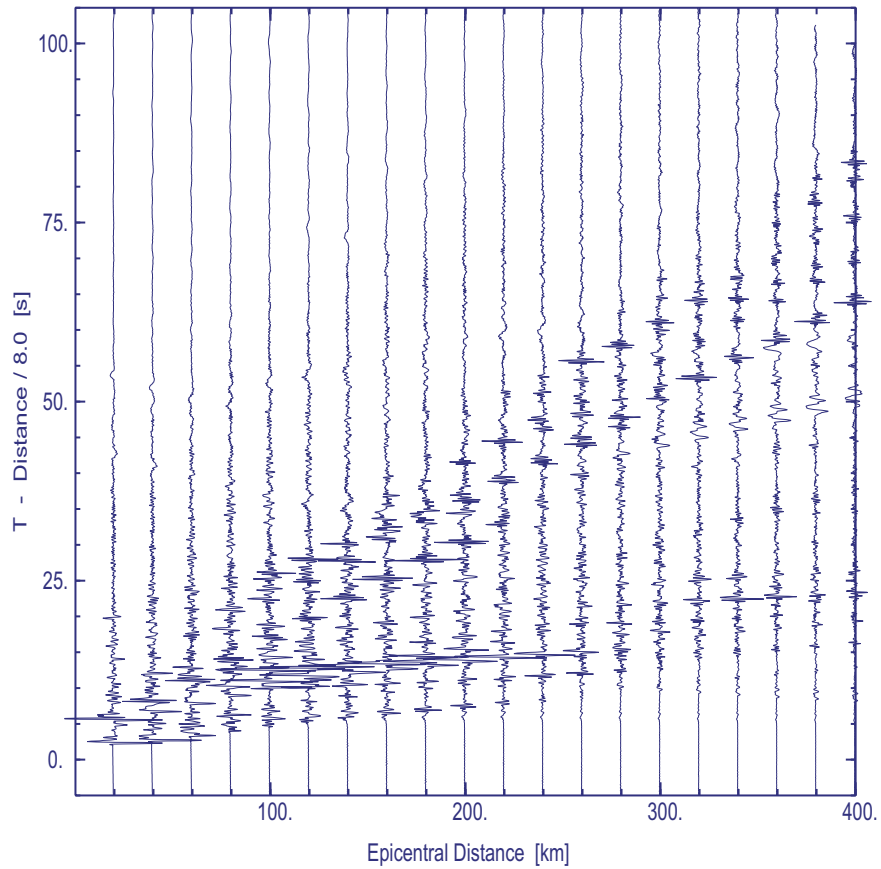


Fig. 3. Reduced travel time seismic section of the radial component ground velocity computed for the 2D model at Colima as a function of distance from the source. In this simulation we did not include the TMVB in the model. Synthetic seismograms are plotted only every 20 km. Compare to Fig. 4a of Furumura and Singh (2002) for Guerrero comparison.

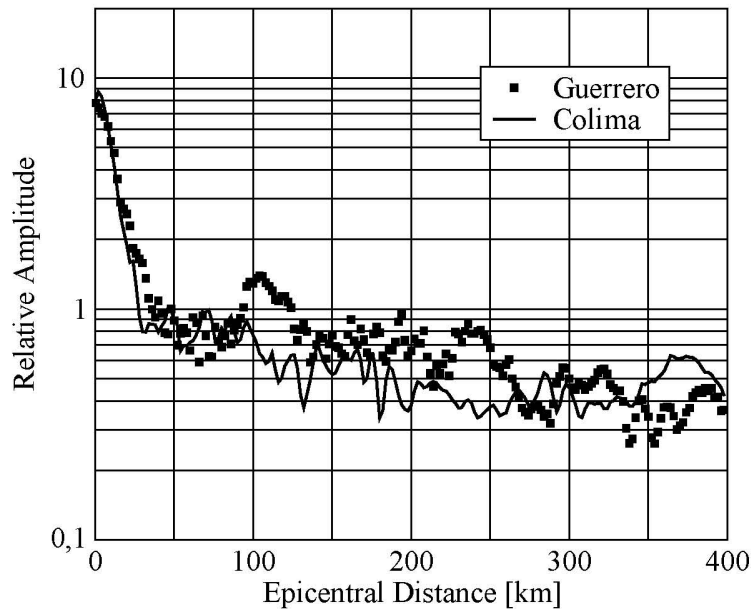


Fig. 4. Relative amplitude of Fourier amplitude spectrum at 0.5 Hz as a function of distance from the source computed for the two cross-sections. S-wave window was Fourier transformed, smoothed by an octave band filter, and the values at 0.5 Hz were normalized by their amplitude at 50 km epicentral distance. These results do not include the TMVB.

The results change significantly when we include in the model the TMVB, at about 50 km from the source in Colima. In Fig. 5 we show the reduced travel time synthetic seismograms computed for this model. The most prominent wavetrains in this figure between 60 y 240 km are Lg phases. These are S waves reflected (SmS phases) several times in the Moho (Kennett, 1985; Campillo, 1990). The amplitudes of all these waves are strongly amplified by the low velocity TMVB.

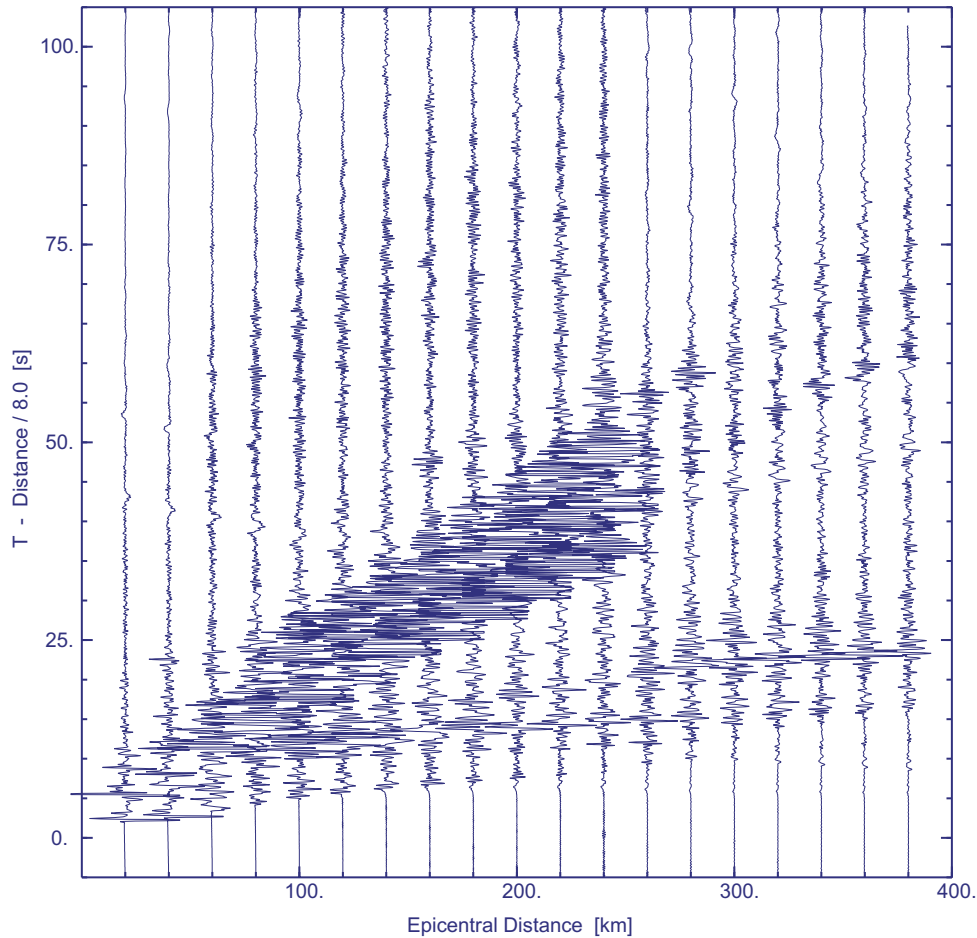


Fig. 5. Reduced travel time seismic section of the radial component ground velocity computed for the 2D model at Colima as a function of distance from the source. This result was computed including the TMVB in the model. Synthetic seismograms are plotted only every 20 km. Compare to Fig. 4a of Furumura and Singh (2002) for Guerrero comparison.

Figure 6 shows the comparison in terms of amplitude of smoothed Fourier spectra at 0.5 Hz between Guerrero and Colima when we include the TMVB in the models. The effect of the TMVB is apparent for the Colima section from 50 km from the source and becomes large for epicentral distances greater than 100 km. This is in very good agreement with the observations of Tejada-Jácome and Chávez-García (2007). The differences in relative amplitude reach a factor 3 at 125 km epicentral distance and remain large for more than 100 km. For epicentral distances larger than 240 km the relative amplitude in Colima decreases sharply, while that at Guerrero increases and becomes larger than at Colima. This is due to the presence of the TMVB; it comes to an end in Colima at 240 km distance while it appears in Guerrero at 220 km distance.

Figure 7 shows the amplitude of smoothed Fourier spectra at 4.0 Hz between Guerrero and Colima models, when we include the TMVB. In general, the results are similar to those in Fig. 6. The curve for Guerrero does not show significant amplification in the TMVB (for epicentral distances larger than 220 km) because attenuation becomes important at this frequency for large distances.

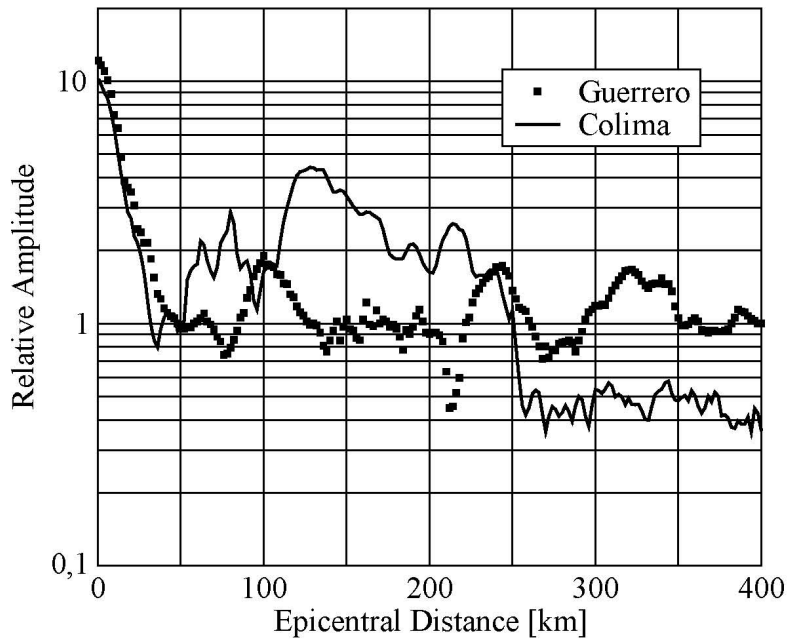


Fig. 6. Relative amplitude of Fourier amplitude spectrum at 0.5 Hz as a function of distance from the source computed for the two cross-sections. S-wave window was Fourier transformed, smoothed by an octave band filter, and the values at 0.5 Hz were normalized by their amplitude at 50 km epicentral distance. These results include the TMVB.

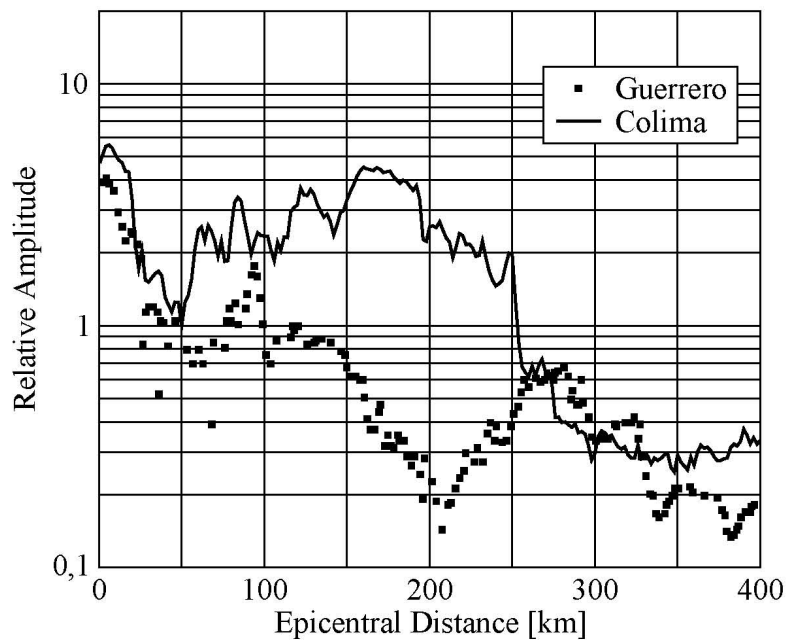


Fig. 7. Relative amplitude of Fourier amplitude spectra at 4.0 Hz as a function of distance from the source computed for the two cross-sections. S-wave window was Fourier transformed, smoothed by an octave band filter, and the values at 0.5 Hz were normalized by their amplitude at 50 km epicentral distance. These results include the TMVB.

Although it would be interesting to compare the sharp decrease in amplitude observed in our model for Colima at 240 km with observations, unfortunately there are no data in that region. The array used by Tejeda-Jácome and Chávez-García (2007) did not extend further than 70 km from the coast. However, recently, the MASE experiment (Clayton et al., 2007, Pérez-Campos et al. 2008) was carried out perpendicular to the coast, from Guerrero to Tamaulipas. It was a very long linear array and included stations to the North of the TMVB. The study of amplitudes along this array could probably be compared with our results.

We can see that the amplification due to the TMVB in Colima appears also in Guerrero, but for larger epicentral distances where the TMVB appears. This suggests that the regional amplification (Ordaz and Singh, 1992) observed in central Mexico is due to the TMVB, as shown by Cárdenas et al. (1997). Thus, even if the regional amplification has been observed and quantified mainly in central Mexico, our results show that this is due to the lack of seismic stations and not to its absence in other sections of the TMVB.

The results we obtained in this study are qualitative. However, currently we are conducting 3D numerical simulations considering more realistic finite faults sources and 3D velocity models in order to compare quantitatively with observations. In our simulations, we will also consider the new model proposed by Pérez-Campos et al. (2008), obtained from receiver functions analysis with data of the MASE experiment. The model is different from that proposed by Valdes et al. (1986) and Valdes and Meyer (1996). The subducting slab is horizontal between 135 and 285 km from the trench (with its uppermost part at about 25 km depth). After that, it falls abruptly with a dip of 75°. With our 3D simulation results, we will also be able to compare the attenuation relations along different profiles in other regions of the subduction zone.

CONCLUSIONS

In this study we compared the differences in seismic attenuation between two 2D models of the crustal structure perpendicular to the subduction zone in Mexico. Our goal was to explain observed differences in attenuation between Colima (in the northern section) and Guerrero (in the southern section). We considered two possibilities to explain those differences: 1) the different geometry of the subduction zone and 2) the presence of the TMVB, closer to the coast. We found that geometry of the subduction does not affect significantly the attenuation between Colima and Guerrero. However, when we include the TMVB, we observe large differences. The presence of the TMVB, a thin soft layer, results in an amplification of peak ground velocity by a factor of 3 for distances larger than 100 km from the source. This result is in very good agreement with the observations of Tejeda-Jácome and Chávez-García (2007). In the Guerrero cross-section, the TMVB is also present, but appears only at distances larger than 220 km from the coast. When the seismic waves generated by subduction earthquakes reach the TMVB, ground motion is also significantly amplified. This is probably the explanation behind the regional amplification in central Mexico studied by Ordaz and Singh (1992) and Cárdenas et al. (1997). The superposition of the regional amplification with the local amplification (Kawase and Aki, 1989; Chávez-García and Bard, 1994; Chávez-García et al. 1994) was behind the large damage observed in Mexico City in 1985 (Singh et al., 1988), as substantiated by Furumura and Kennet, 1998 and Chávez-García and Salazar (2002) among others. Our results show that at least the regional amplification may increase seismic motion anywhere within the TMVB, and therefore, this factor should be included in future evaluations of seismic hazard in Mexico. New 3D simulations with realistic finite fault source and 3D velocity structures would be very helpful to study attenuation in different regions of the subduction zone.

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REFERENCES

- Alesina, D., R.L. Woodward and R.K. Sneider [1996]. "Shear wave velocity structure in North America from large-scale waveform inversions of surface waves. *J. Geophys. Res.* 101, 15,969-15,986.
- Bandy, W., C. Mortera-Gutierrez, J. Urrutí-Fukugauchi, and T.W.C. Hilde [1995]. "The subduction Rivera-Cocos plate boundary: where is it, what is it, and what is its relationship to the Colima rift?, *Geophys. Res. Lett.* 22, 3075-3078.
- Bandy, W., Kostoglodov, A. Hurtado-Díz, and M. Mena [1999]. "Structure of the southern Jalisco subduction zone, Mexico, as inferred from gravity and seismicity, *Geophys. Int.* 38, 127-136.
- Campillo, M. [1990]. "Propagation and attenuation characteristics of the crustal phase Lg, *Pure Appl. Geophys.* 132, 1-9.
- Cárdenas, M., F.J.Chávez-García, and A. Gusev [1997]. "Regional amplification of ground motion in central Mexico. Results from coda-length magnitude data and preliminary modeling, *J. Seismol.* 1, 341-355.

- Chávez-García, F.J. y P.-Y. Bard [1994]. "Site effects in Mexico City eight years after the September 1985 Michoacan earthquakes, *Soil Dyn. & Earthq. Engrg.* 13, 229-247.
- Chávez-García, F.J., F.J. Sánchez-Sesma, M. Campillo y P.-Y. Bard [1994]. "El terremoto de Michoacán de Septiembre de 1985: efectos de fuente trayecto y sitio, en E. Buforn, A. Udías y R. Madariaga (editores) *Mecanismo focal de los terremotos, Física de la Tierra* No. 6, Editorial Complutense, 157-200.
- Chávez-García, F. J. and Salazar, L. [2002]. "Strong motion in central Mexico: A model based on data analysis and simple modeling, *Bull. Seism. Soc. Am.* 92, 3087-3101.
- Cerjan, C., D. Kosloff, R. Kosloff, R, and M. Reshef. [1985]. "A non reflecting boundary condition for discrete acoustic and elastic wave equations. *Geophysics*, 50, 705--708.
- Clayton, R., P. M. Davis, and X. Pérez-Campos [2007]. "Seismic structure of the subducted Cocos plate. EOS, Transactions, American Geophysical Union 88 [23], Jt. Assem. Suppl. Abstract T32A-01.
- DeMets, C. and S. Stein [1990]. "Present-day kinematics of the Rivera plate and implications for tectonics of southwestern Mexico, *J. Geophys. Res.* 95, 21,931-21,948.
- Furumura, T. and Takenaka, H. [1996]. "2.5-D modeling of elastic waves using the pseudospectral method, *Geophys. J. Int.* 124, 820--832.
- Furumura, T., and B.L.N. Kennett [1998]. "On the nature of regional seismic phases- III. The influence of crustal heterogeneity on the wavefield for subduction earthquakes: the 1985 Michoacan and 1995 Copala, Guerrero, Mexico earthquakes. *Geophys. J. Int.*, 135, 1060-1084.
- Furumura T. and S.K. Singh [2002] Regional wave propagation from Mexican subduction zone earthquakes: The attenuation functions for interplate and in-slab events, *Bull. Seism. Soc. Am.* 92, 2110-2125.
- García D., S.K. Singh, M. Herráiz, M. Ordaz, and J.F. Pacheco [2005]. "In-slab earthquakes of central Mexico: peak ground-motion parameters and response spectra, *Bull. Seism. Soc. Am.* 95, 2272-2282.
- Gomberg, J., and Masters, T.G., 1988a, Waveform modeling using locked-mode synthetic and differential seismograms--application to determination of the structure of Mexico: *Geophysical Journal of the Royal Astronomical Society*, v. 94, p. 193-218.
- Gomberg, J., Priestley, K., Masters, T.G., and Brune, J., 1988b, The structure of the crust and upper mantle of northern Mexico: *Geophysical Journal of the Royal Astronomical Society*, v. 94, p. 1-20.
- Herrmann, R.B. [1979] S-wave generation by dislocation source: a numerical study, *Bull. Seism. Soc. Am.* 69, 1-15.
- Kawase, H., and K. Aki [1989]. "A study on the response of a soft basin for incident S, P, and Rayleigh waves with spectral reference to the long duration observed in Mexico City, *Bull. Seism. Soc. Am.*, 79, 1361-1382.
- Kennett, B. L. N. [1985]. "On regional S. *Bull. Seism. Soc. Am.* 75, 1077-1086.
- Kosloff, D. and Baysal, E. [1982]. "Forward modelling by a Fourier method, *Geophysics* 47, 1402-1412.
- Kosloff, D., M. Reshef, and D. Loewenthal [1984]. "Elastic wave calculation by the Fourier method, *Bull. Seism. Soc. Am.* 74, 875-891.
- Kostoglodov, V. and J.F. Pacheco [1999]. "Cien años de sismicidad en México, Instituto de Geofísica, UNAM.
- Molina-Garza, R. and Urrutia-Fucugauchi, J. [1994]. "Deep crustal structure of central Mexico derived from interpretation of Bouguer gravity anomaly data. *J. Geodynamics*, 17, 181-201.
- Nuñez-Cornú F.J., G. Reyes-Dávila, M. Rutz, E. Trejo, M.A. Camarena, and C.A. Ramírez [2004]. "The 2003 Armería, Mexico earthquake [Mw=7.4]: mainshock and early aftershocks, *Seism. Res. Lett.* 75, 734-743.

Ordaz, M., J.M. Jara, and S.K. Singh [1989]. “Riesgo sísmico y espectros de diseño en el Estado de Guerrero, *Mem. VIII Congr. Nac. Ing. Sísmica*, Acapulco, D40-D56 [in Spanish]. “

Ordaz, M., and Singh, S. K. [1992]. “Source spectra and spectral attenuation of seismic waves from Mexican earthquakes, and evidence of amplification in the hill zone of Mexico City, *Bull. Seism. Soc. Am.* 82, 24-43.

Pacheco, J., S.K. Singh, J. Domínguez, A. Hurtado, L. Quintanar, Z. Jiménez, J. Yamamoto, C. Gutierrez, M. Santoyo, W. Bandy, M. Guzmán, V. Kostoglodov, G. Reyes, and C. Ramírez [1997]. “The October 9, 1995 Colima-Jalisco, Mexico earthquake [MW 8]: an aftershock study and a comparison of this earthquake with those of 1932, *Geophys. Res. Lett.* 24, 2223-2226.

Pardo and Suarez [1995]. “Shape of the subducted Rivera and Cocos plates in southern Mexico; seismic and tectonic implications, *J. Geophys. Res.* 100, 12357-12373.

Pérez-Campos, X., Y.H. Kim, A. Husker, P.M. Davis, R.W. Clayton, A. Iglesias, J.F. Pacheco, S.K. Singh, V.C. Mena, and M. Gurnis [2008]. “Horizontal subduction and truncation of the Cocos plate beneath central Mexico”, *Geophys. Res. Lett.* 35.

Singh, S.K., E. Mena, and R. Castro [1988]. “Some aspects of source characteristics of the 19 September 1985 Michoacan earthquake and ground motion in and near Mexico City from strong motion data. *Bull. Seism. Soc. Am.* 78, 451-477.

Tejeda-Jácome, J. and F.J. Chávez-García [2007]. “Empirical ground-motion estimation equations in Colima from weak motion records, *ISET J. of Earthq. Tech.* 44, in press.

Valdes, C., Mooney, W., Singh, S. K., Meyer, R., Lomnitz, C., Luetgert, J., Helsley, C., Lewis, B., and Mena. M. [1986]. “Crustal structure of Oaxaca, Mexico, from seismic refraction measurements, *Bull. Seism. Soc. Am.* 76, 547-563.

Valdes, C. and Meyer, R. [1996]. “Seismic structure between the Pacific coast and Mexico City from the Petatlan earthquake [Ms=7.6] aftershocks, *Geofis. Int.* 35, 377-401.

Yagi Y., T. Mikumo, F. Pacheco, and G. Reyes [2004]. “Source rupture process of the Tecomán, Colima, Mexico earthquake of 22 January 2003 determined by joint inversion of teleseismic body-wave and near-source data, *Bull. Seism. Soc. Am.* 94, 1795-1807.