

# Seismic velocity structure of the Guerrero gap, Mexico

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Received: August 26, 2005; accepted: April 4, 2006

## RESUMEN

Se obtiene la estructura bidimensional de velocidades sísmicas de la brecha de Guerrero aplicando el método de mínimos cuadrados amortiguados a los datos de la sismicidad local registrada por una red telemétrica situada en la costa, ubicada en la zona de subducción de la placa de Cocos. La región se parametrizó con una malla de 64 cubos en seis capas, un total de 384 bloques. Los resultados de esta inversión tridimensional (3-D) mostraron una diferencia de velocidad de onda P, entre bloques adyacentes y paralelos a la costa, no mayor de 0.25 km/s, mostrando una simetría bidimensional. Se utilizó una segunda inversión bidimensional (2-D), que toma en cuenta la similitud de velocidad de onda P de bandas paralelas a la costa, para generar una estructura de megabloques. Una inversión final muestra una estructura de velocidades de onda P con valores de 5.4 a 8.2 km/s, y valores para onda S entre 3.2 y 4.7 km/s, con una corteza continental de ~32 km de espesor, compuesta de cuatro megabloques planos con un intervalo de velocidad de onda P de 5.4 a 7.1 km/s. El Moho se localiza a una profundidad de ~32 km sobre una cuña del manto entre la corteza continental y la corteza oceánica. La corteza oceánica subducente se compone de tres capas (7.2-7.7 km/s), que presentan un ángulo de buzamiento de 26°. Un cambio importante de velocidad (7.2 a 7.6 km/s) a una profundidad de 30 km hace pensar en un cambio de fase de basalto a eclogita. El manto tiene una velocidad media de 8.2 km/s. El nuevo modelo de velocidades redujo el error de localización de la sismicidad local, la cual se ajusta mejor a las características de la brecha de Guerrero.

**PALABRAS CLAVE:** Estructura de velocidades sísmicas, bloques de velocidad, inversión sísmica.

## ABSTRACT

A two-dimensional velocity structure of the Guerrero gap was obtained by applying a damped least square method to hypocenters of local seismicity recorded by a telemetric network situated on the Guerrero coast, above Cocos plate subduction zone. The region was parameterized by a mesh of 64 cubes in six layers, a total of 384 blocks. The results of 3-D inversion showed that differences of P-wave velocity values among blocks along the strike of the subduction zone were ~0.25 km/s, effectively showing a two-dimensional symmetry. A 2-D inversion taking into account velocity similarities among the 2-D bands generated megablocks. A final inversion procedure yields P-wave velocity values ranging from 5.4 to 8.2 km/s, and S-wave values from 3.2 and 4.7 km/s, suggesting a continental crust with a thickness of ~32 km composed of four flat megablocks with a P-wave velocity interval of 5.4 to 7.1 km/s. The Moho interface lies at ~32 km depth and above a mantle wedge between continental and oceanic crust. The downgoing oceanic crust has three layers (7.2-7.7 km/s), dipping at an angle of ~26°. A sharp velocity change at a depth of ~30 km suggests a phase change from basalt to eclogite (7.2 to 7.6 km/s). The mantle has an average velocity of 8.2 km/s. The new velocity model reduced the error in locations and fits better the characteristics of the Guerrero gap.

**KEY WORDS:** Seismic velocity structure, velocity blocks, seismic inversion.

## INTRODUCTION

The tectonic regime in the coast of Guerrero in central Mexico is dominated by subduction of the Cocos plate beneath the North American plate. The subducted slab reaches a maximum seismic depth of about 60 km (Suárez *et al.*, 1990). The Guerrero coast region is marked by a well-defined seismic gap in which no large earthquake have occurred since 1908 (Suárez *et al.*, 1990). A large earthquake may take place here (e.g., Nishenko and Singh, 1987), which could seriously affect Mexico City. This region is seismically defined by an active thrust interface, which extends to an anomalously shallow depth of ~25 km (Nishenko and Singh, 1987; Dewey and Suárez, 1991; Suárez and Sánchez, 1996).

The Institute of Geophysics of the National Autonomous University of Mexico (UNAM) installed a telemetric seismic network composed of eight vertical-component seismometers of 1 Hz and one central station with three components (1 Hz), to monitor the seismic activity in the Guerrero gap before, during and after a large earthquake. This network spans an area between 100.24° and 101.38° W (Figure 1a). An average of five events was registered each day. Timing is controlled by a common GPS time base, P and S arrival times were read with an accuracy of one hundredth of a second. All events were routinely located using HYPO71PC (Lee and Valdés, 1985) with a flat-layer velocity model proposed by Suárez *et al.* (1992). A total of 6900 events have been recorded from September 1987 to July 1995, with magnitudes ( $M_L$ )

ranging from 1.0 to 4.0. Along the coastline the distribution of earthquakes is concentrated along two seismic bands separated by 8 km (Figures 1a and 1b). The coastal band shows hypocenters with depths ranging between 10 and 25 km, dominated by thrust mechanisms with northeast dipping faults at an angle  $\sim 12^\circ$  (Suárez *et al.*, 1990). The second seismic band farther inland exhibits hypocentral depths ranging between 32 and 42 km, and shows a

combination of reverse and normal faulting mechanisms (Suárez *et al.*, 1990).

The geometry of the subducted slab in this region features a shallow dipping plate ( $\sim 12^\circ$ ) beneath North American reaching a depth of  $\sim 40$  km. The slab is then bent upward, and follows a subhorizontal trajectory that extends inland at a depth of  $\sim 50$  km (Suárez *et al.*, 1990)

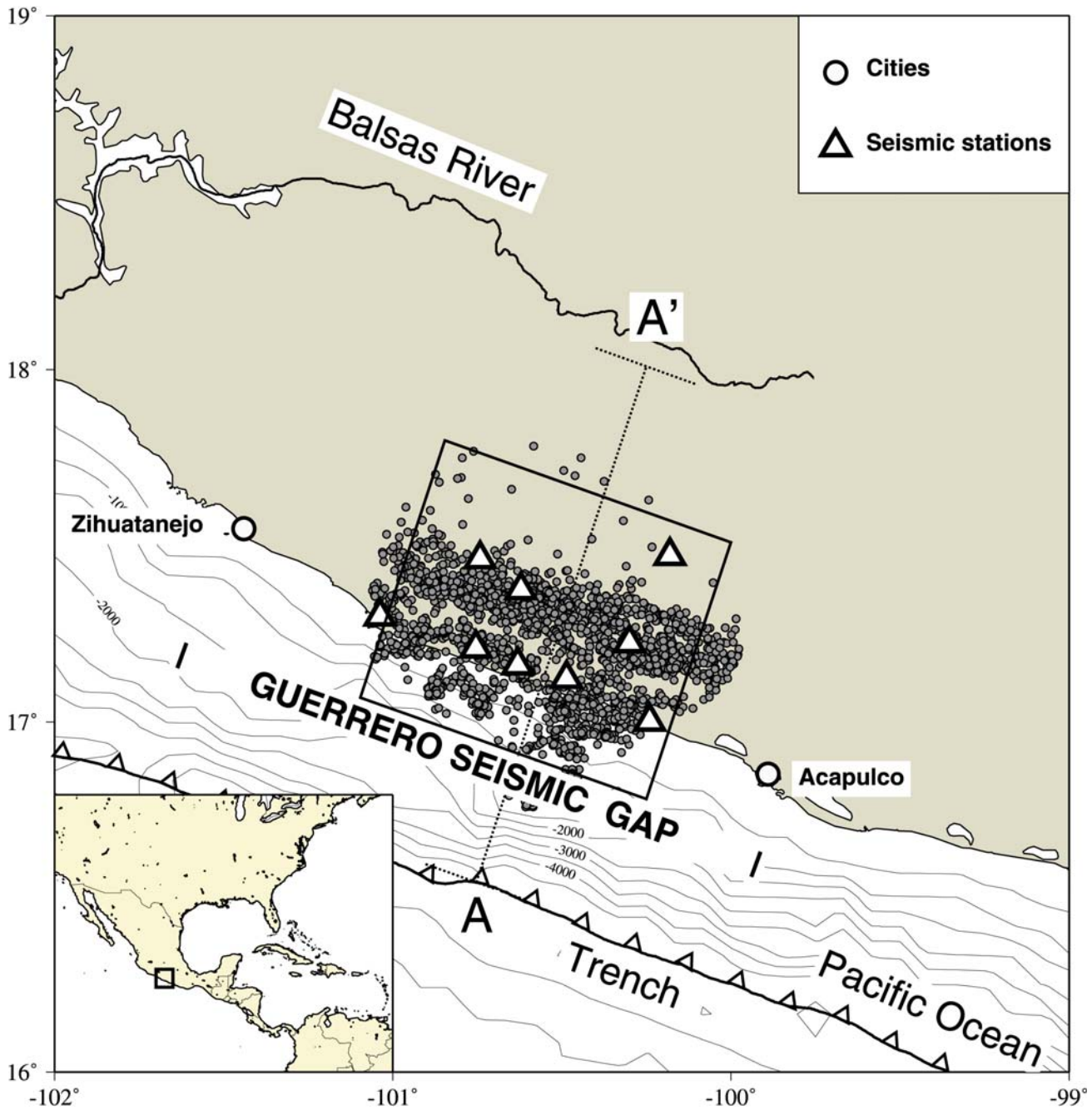


Fig. 1a. Seismicity recorded by the Guerrero seismic telemetric network, from September 1987 to August 1992. From a total of 6900 micro-earthquakes, the figure only show the 2350 events (dots) with hypocentral error less to 0.5 km, and coverage angle less than  $180^\circ$ , distributed on two seismic bands along the coast. Triangles indicate the location of the seismic stations and the dashed line indicates the location of profile A-A' (Figure 1b). Mayor cities are shown as squares. The square around of seismicity indicates the area where inversion method is applied.

and Domínguez, 1991). Pardo and Suárez (1995) constructed the 3-D geometry of the entire subducting Cocos plate along the Mexican coastline.

Various workers have studied the velocity structure of this region and adjacent areas. Lewis and Snodman (1979), Núñez-Cornú *et al.* (1992), Valdés-González (1993) and Valdés-González and Meyer (1996) applied different refraction ray trace methods to seismic data to obtain seismic velocity structure of the oceanic crust, along and normal to the coastline. Suárez *et al.* (1990), Araujo (1991) and Domínguez (1991) determined the geometry of the 2-D subducting slab along the Guerrero coastline using local information. Suárez *et al.* (1992) determined a one-dimensional (1D) seismic velocity model. However, there are no specific studies within the Guerrero gap that study in detail the tectonic characteristics of this region. The purpose of this work is to define the structure of the oceanic and continental lithosphere beneath the Guerrero coastline, applying a damped least square method (e.g. Aki and Lee, 1976; Roecker, 1982). We use local telemetric data to obtain the seismic velocity structure across the Guerrero gap.

### INVERSION THEORY

The algorithm of the method proposed by Aki and Lee (1976) and Aki *et al.* (1977), as modified by Roecker (1982), is used to determine crustal velocity structure under the Guerrero coast. This method uses arrival times

of P and S-waves of local and teleseismic events. A similar methodology has been used by several authors to study the structure of other tectonic environments (e.g., Roecker, 1982; Roecker, Yeh and Tsai, 1987; Aber and Roecker, 1991; Comte *et al.*, 1994).

The inversion applies an iterative, non-linear formulation (Tarantola and Valette, 1982). Techniques of progressive inversion and parameter separation were also incorporated (Roecker, 1982). The earthquakes are relocated prior to perturbing the structure and the hypocentral parameters are decoupled from the velocity parameters when solving for structural perturbation. Intrinsic smoothing results from the use of several sizes blocks. The covariance matrix of the model is diagonal, and the size of this diagonal element had to be an order of magnitude larger than what might be presumed from considerations of a priori uncertainties, in order to be able to stabilize the solution.

To initiate the inversion process, the lithosphere beneath Guerrero gap was parameterized by a set of layers bound by horizontal interfaces, each of these horizontal layers is divided into a grid of rectangular prisms or blocks by two orthogonal sets of vertical interfaces. The one-dimensional or three-dimensional velocity structure is determined through minimizing, in a damped least square sense, the travel time residual of P and S-waves from earthquakes by adjusting the Earth model and the hypocentral coordinates of the earthquake events. P and

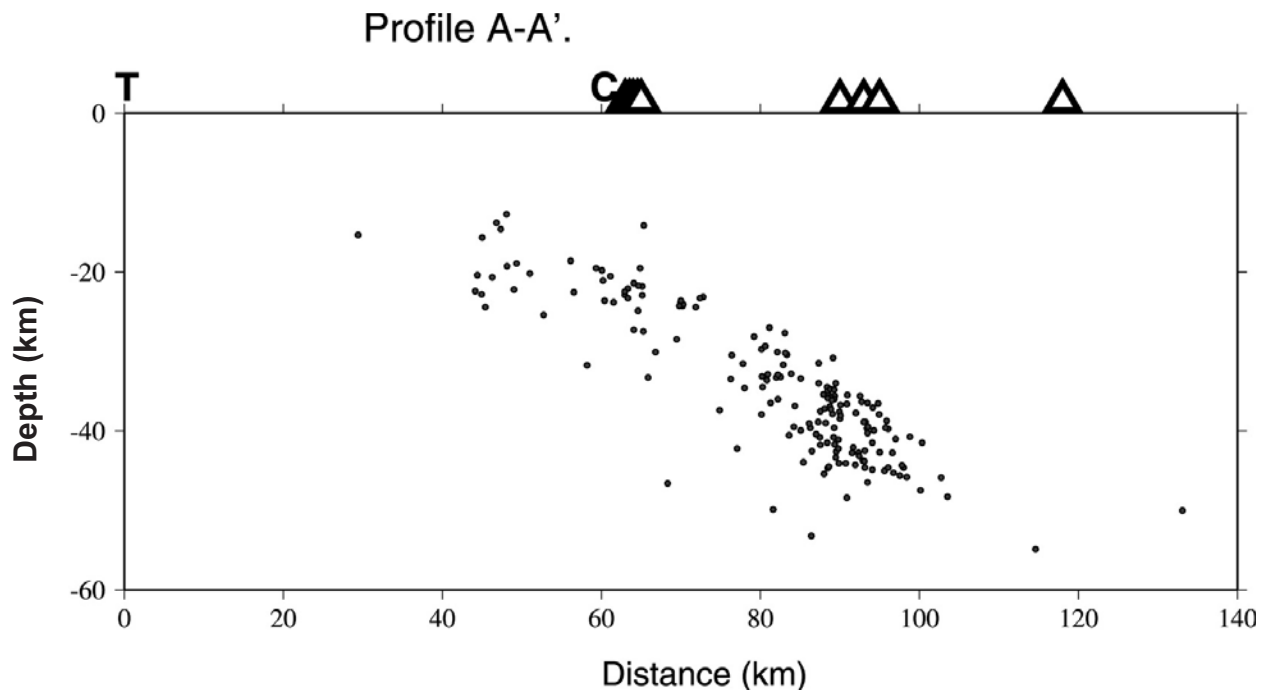


Fig. 1b. Seismic profile along A-A' that shows a first seismic band along the coastline, reflecting the zone of seismogenic coupling, and a second and deeper band forms of intraplate events located a depth of 28 to 50 km. The C letter indicates the position of coastline, T indicates the position of the trench, and white triangles show the profile position of seismic stations.

S-waves velocities are determined as independent parameters within each block. Approximate ray-tracing is used to provide a reasonable estimate of travel time through a laterally varying structure, thus reducing bias introduced and by non-linearity and the choice of a particular starting model (Thurber, 1983; Aki and Lee, 1976; Aki et al., 1977; Roecker, 1982).

## SEISMIC VELOCITY STRUCTURE INVERSION

### 1. One-dimensional inversion

The first step in the inversion process is obtaining a one-dimensional seismic velocity model. An early velocity model in the area of the Guerrero coast was obtained by Suárez et al. (1992), applying the minimum apparent velocity of refracted waves (e.g. Matumoto, 1977). This model was used as the initial velocity model for one-dimensional inversion.

The results of one-dimensional velocity inversion show P-wave values similar to those obtained by Suárez et al. (1990), particularly for the intermediate layers (12.5-45 km) which have the best resolution (between 0.69-0.87), and where most of the seismicity is located. The resolution of deeper layers (40-50 km) is low (between 0.01 and 0.06). They also show the largest errors (0.47 km/s-0.48 km/s). This is due to the fact that few rays go through them. Similarly, the top layer (0.0-10.1 km) is poorly resolved (0.36) with a resulting error of 0.20 km/s. The resulting P-wave velocity model is similar to that obtained by Suárez et al. (1992, Figure 2), with a difference of not more than 0.4 km/s.

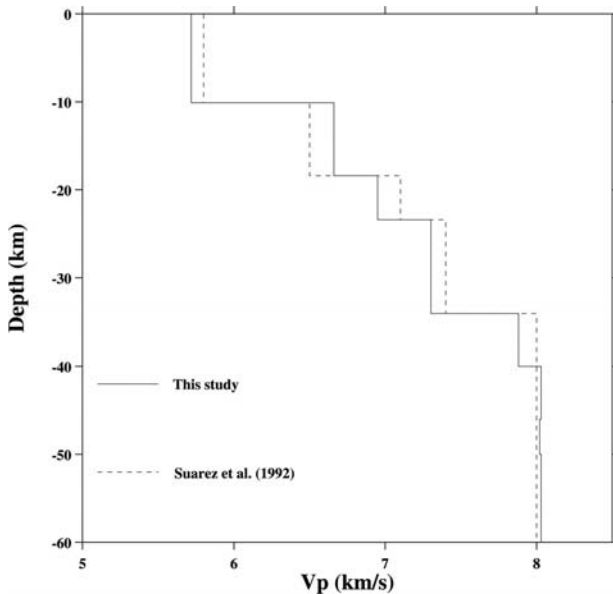


Fig. 2. One-dimensional velocity models of the Guerrero gap; the dashed line is the model of Suárez et al. (1992) and solid line is the model obtained in this study.

### 2. Three-dimensional inversion

The one-dimensional velocity structure is used as the initial model for the three-dimensional inversion process. A three-dimensional mesh is defined by 64 rectangular blocks in each one of the 6 layers. Each block has 10 km by side and a similar thickness to the one-dimensional velocity model (Figure 2). The mesh has a strike of  $\sim 340^\circ$ . The resulting three-dimensional velocity structure is shown in the Figure 3; we observed no large differences among velocity values of horizontally adjacent blocks parallel to the coastline. In general, the differences of P-wave velocity values are equal or less to 0.25 km/s, and 0.11 km/s for S-waves. For example, in the third layer (18.4-23.4 km, Figure 3), the difference between adjacent blocks is 0.06 to 0.18 km/s (P-wave), and 0.01 to 0.06 km/s for S-wave. The similarity of seismic velocities in Guerrero along the strike of the coastline suggest that the geological characteristics only change along the convergence between the Cocos and North America plates, in agreement with previous studies (e.g., Suárez et al., 1990; Valdés, 1993; Valdés-González and Meyer, 1996; Kostoglodov et al., 1996).

However, these results are not of uniform quality because resolution in some block is low, as they are sampled by not enough rays. To improve the resolution, we merged several cubes along the coastline to form bands. The results improved the resolution in each block or band by  $\sim 40\%$  and reduced the error values by  $\sim 10\%$  compared to the three-dimensional velocity structure (Figure 3). After join in blockbands parallel to the coast the cubes having the same speed values, we draw a vertical projection (following AA') which we present in the Figure 4. Grouping several blockbands from the "megastructure" shown on this figure, to define larger blocks (hereafter named "megablocks") of similar wave speed, we inverted again to get the final velocity model. In the next section we explain the results.

### 3. Two-dimensional inversion

Different two-dimensional distributions of megablocks were tested to determine the best model parameter fit, the resolution and the error in each megablock with special attention for the velocity structures of adjacent areas, e. g. Valdés-González and Meyer (1996) and Suárez et al. (1992).

Valdés-González and Meyer (1996) found a compressional and shear velocity structure of the subduction zone between Petatlán and Mexico City (length of  $\sim 450$  km and depth of 110 km) and along the coast of the State of Guerrero, by applying a seismic refraction method to aftershock data of the  $M_s=7.6$  Petatlán, Guerrero earthquake of March 14, 1979. This model consists of a two-dimensional ocean to continent structure featuring a

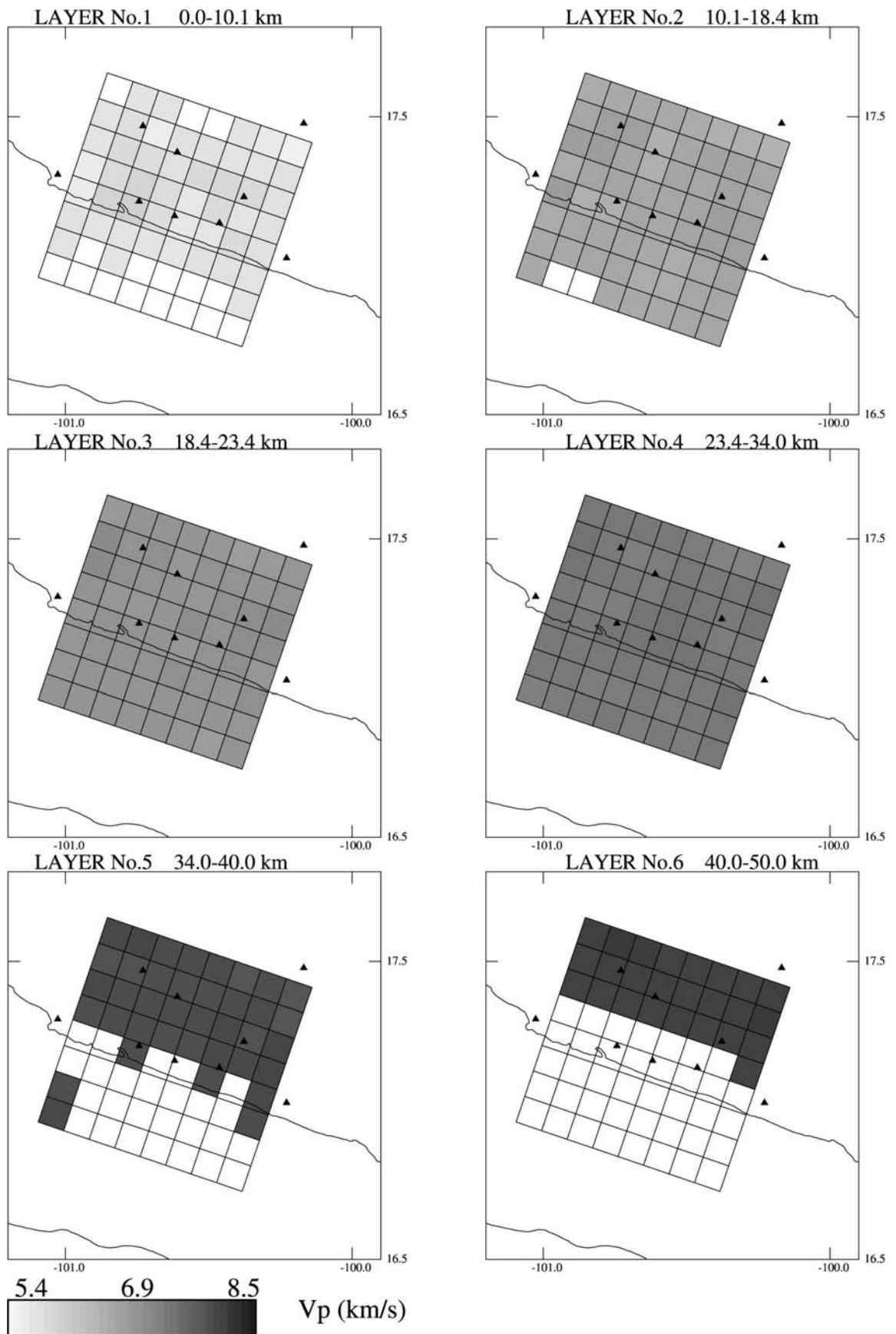


Fig. 3. Results of the three-dimensional inversion to P-wave velocity, using a mesh of 384 cubes with 10 kilometers long per side in plane and thickness like to the one-dimensional model from the Figure 2. Black little triangles are seismic stations.

continental block of three flat crustal layers (5.3 to 6.4 km/s  $V_p$  values) with the Moho at 45 km depth. The oceanic crust is composed of two layers with 8 km total thickness dipping  $10^\circ$  (6.4 to 7.4 km/s  $V_p$  values). The upper mantle-oceanic crust transition has a thickness of  $\sim 55$  km (7.9-8.1 km/s  $V_p$  values), and the oceanic upper mantle has a  $V_p$  of  $\sim 8.2$  (km/s).

Our best results are shown in Figure 5. After establishing the final distribution of megablocks, the damping value was modified,  $\theta$  is a weight equal to  $\sqrt{\sigma^2 / \sigma_m^2}$ , where  $\sigma^2$  is the data variance and  $\sigma_m^2$  is the model variance. The best fit was obtained for  $\theta = 25\ 000$ .

The final seismic velocity structure (Figure 5) features a continental crust with four flat layers. The first has a thickness of 3 km (P1), which is poorly resolved (0.19) because the rays that cross it are perpendicular to the interface. The next layers (P2, P3 and P4) have a thickness of 10 km each and a resolution of between 0.84 and 0.93.

The Cocos plate is defined by three megablocks P6, P7 and P8, each with an average thickness of 5 km and resolution values of 0.83, 0.67 and 0.85 respectively. P9 is the deepest block with a poor resolution of 0.53. The velocity uncertainties are between 0.07 to 0.29 km/s, if we neglect the blocks that have poor resolution (P1 and P9), the velocity uncertainty interval is 0.07-0.25 km/s. The results for S-wave velocity are similar to those for P-wave velocity, with a resolution values less than  $\sim 23\%$  and error values less  $\sim 68\%$ , in relation to those values obtained for the P-wave model. The difference is due to the fact that the inversion scheme uses the S wave velocity to refine the P-wave velocity model (Roecker, 1982).

#### 4. Resolution of the velocity model

In order to verify the robustness of the results, resolution and mean errors were tested using synthetic arrival time data of P and S-waves generated with the seismic velocity model, and the mesh of Figure 5. The arrival times were perturbed with random noise (time delays with a mean of 0.1 s and a standard deviation of 0.2 s) introduced in the observations on all P and S arrival times.

The inversion program was applied to these synthetic data and the seismic velocity structure was confirmed (Figure 6). In general, the resolution and errors observed were better for the original model of the Figure 5, with an interval resolution for P-waves of (0.48 - 0.99), and (0.35 - 0.97) for S-waves, and an interval error for P-waves of (0.03 - 0.13) km/s, and (0.02 - 0.05) km/s for S-waves. The observed change in P and S wave velocity values is  $\sim 1\%$ , i.e. not more than 0.05 km/s for P-waves and 0.02 km/s for S-waves (Figure 6). These results show the

robustness of the initial two-dimensional velocity structure obtained with local seismic data.

## DISCUSSION

The distribution of seismicity relative to the network provides an adequate resolution of all megablocks in the structure. Often few seismic rays sample the blocks or cross them perpendicularly. Still, the results allow to define clearly some tectonic structures (Figure 5): (1) The oceanic crust of the subducting Cocos plate (P6, P7 and P8 blocks), with a dip of  $\sim 26^\circ$  as reported in large shallow thrust events by Pardo and Suárez (1995). (2) The Moho discontinuity (interface between P4 and P5) at a depth of  $\sim 32$  km; (3) the upper mantle (P9).

The velocity structures shown on Figure 5 agree with the distribution of megablocks for velocity structures in Oaxaca (Valdés *et al.*, 1986) and Guerrero (Valdés-González and Meyer, 1996). The Oaxaca structure velocity is a seismic refraction and gravity model with 500 km length and 80 km in depth, composed by a continental crust (three layers with a thickness of  $\sim 45$  km and  $V_p$  interval of 4.3-7.0 km/s), the Moho is located at a depth of  $\sim 45$  km. The oceanic crust is composed of two layer with a total thickness of 8 km, over a transitional layer with a variable thickness (from 13 to 20 km), dipping with an angle of  $\sim 10^\circ$ . Under this structure there is the upper mantle megablock with  $V_p$  of 7.6 km/s. There are dimensional and velocity differences between both models. The transitional layer is similar to P8 block from the Figure 5. Only the distribution of the blocks is similar.

The Guerrero refraction model (Valdés-González and Meyer, 1996) is quite different. It does not provide enough detail in the contact zone beneath the Guerrero coastline. However, there are some similarities. Both models feature a continental crust of 4 flat layers and an oceanic crust of two thin layers over a high velocity block in the upper mantle.

Lewis and Snydsman (1979) defined two horizontal layers in the oceanic crust, south of Acapulco. The first layer has  $V_p$  between 4.2 and 6.2 km/s, and the second one has a  $V_p$  interval of 6.8-7.0 km/s. These two layers have a total thickness of 6 km, and may represent the upper layer of the oceanic crust (P6) shown in Figure 5, this value is possibly influenced by sediments.

The velocity change in the upper oceanic layer is possibly due to a transitional zone caused by a phase change from gabbro to eclogite, from P6 to P7 blocks (Figure 7), as in Kirby *et al.* (1996), Hacker (1996) and Rushmer (1996). Eclogite formation induced by dehydration of a warm slab (Heat flow  $> 75$  mW/m<sup>2</sup>), causes the slow young descending slab (age  $< 15$ -25 Ma),

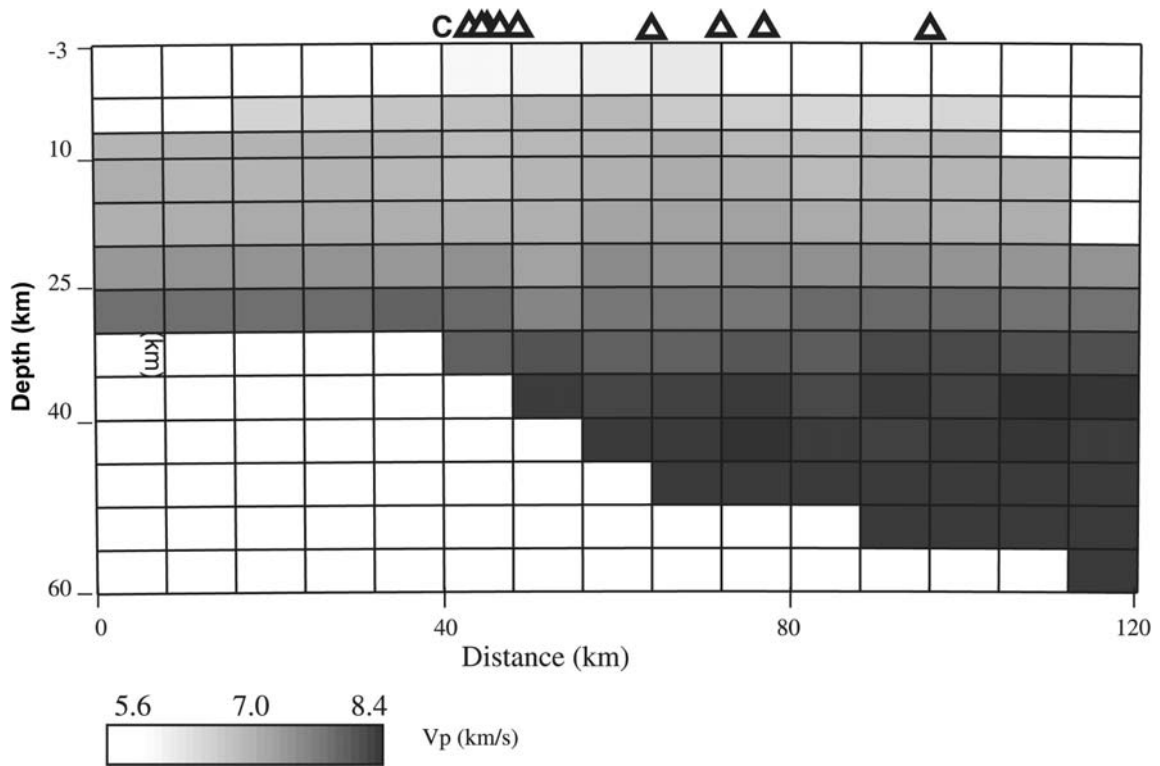


Fig. 4. Resulting two-dimensional velocity structure parametrized using bands parallel to the coast. The gray scale indicate Vp values from 5.6 to 8.4 km/s. Symbols like before figures.

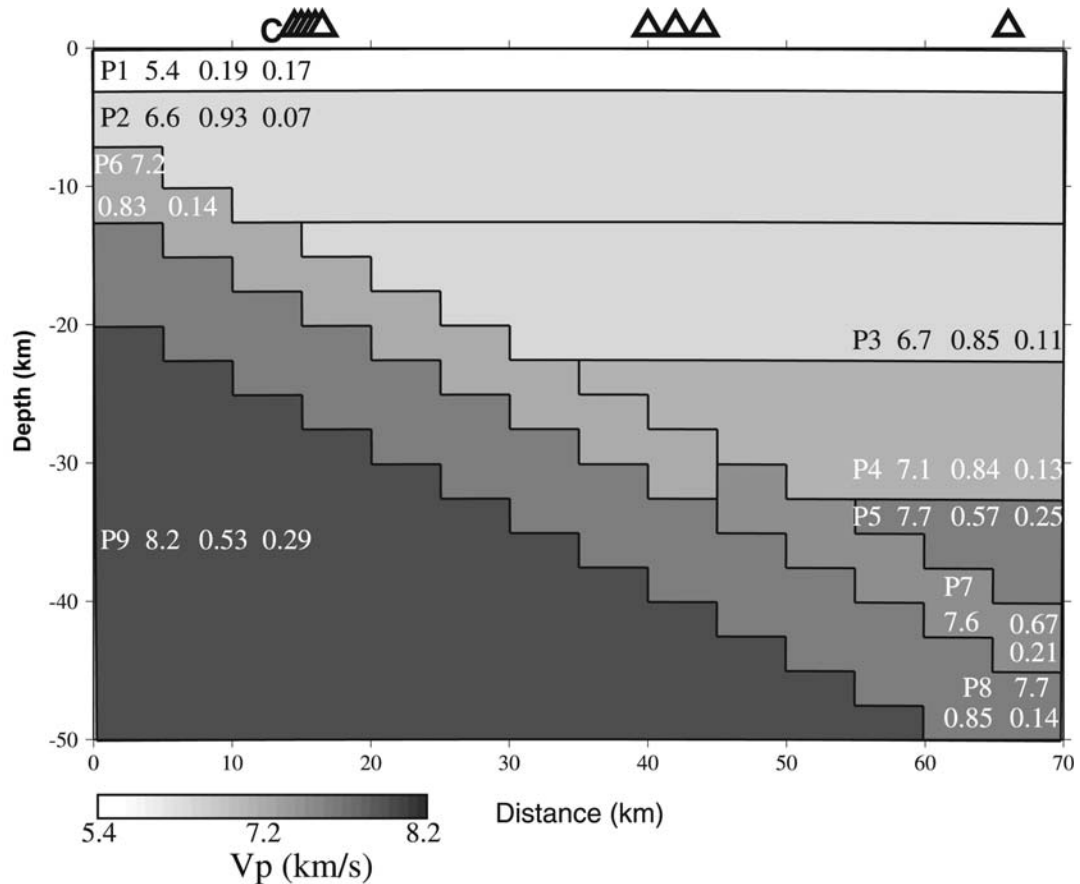


Figure 5. Results of the inversion process for P-wave velocity using a megablocks distribution structure. Each block is labeled from P1 to P9 and for each megablock the P-wave velocity, resolution and mean error is shown.

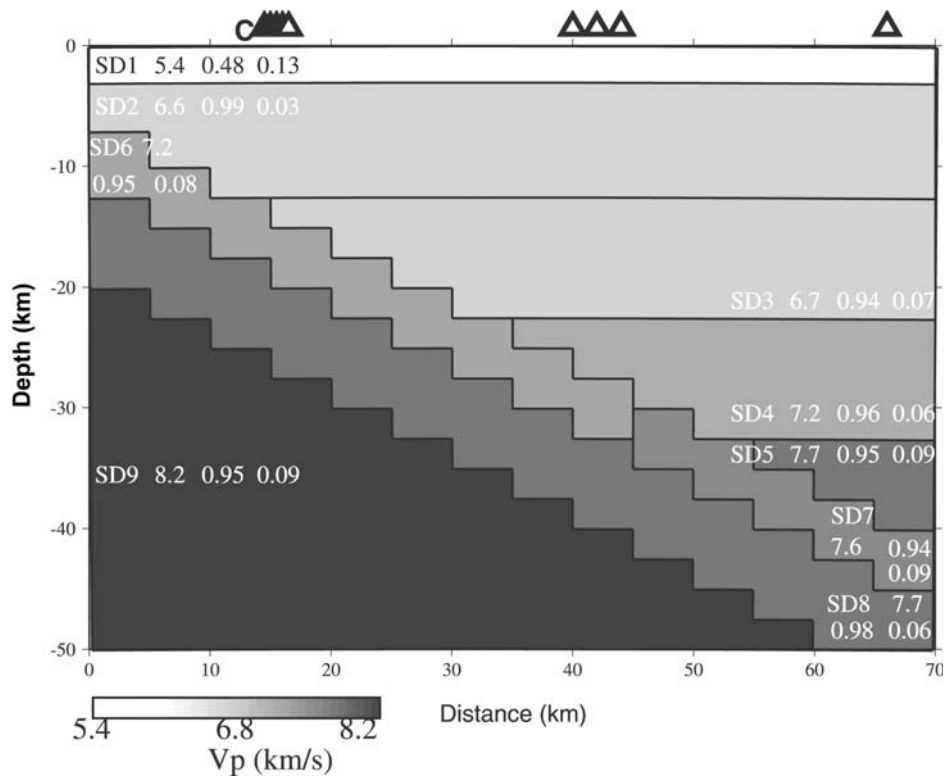


Fig. 6. Results of the test of the inversion results for P-wave velocity using synthetic data from the perturbed arrival times. Both the resolution values and the estimated errors confirm that the data are adequate to resolve the structure (Figure 5). This figure only shows the results of P-wave velocity for each megablock (SD1 to SD9).

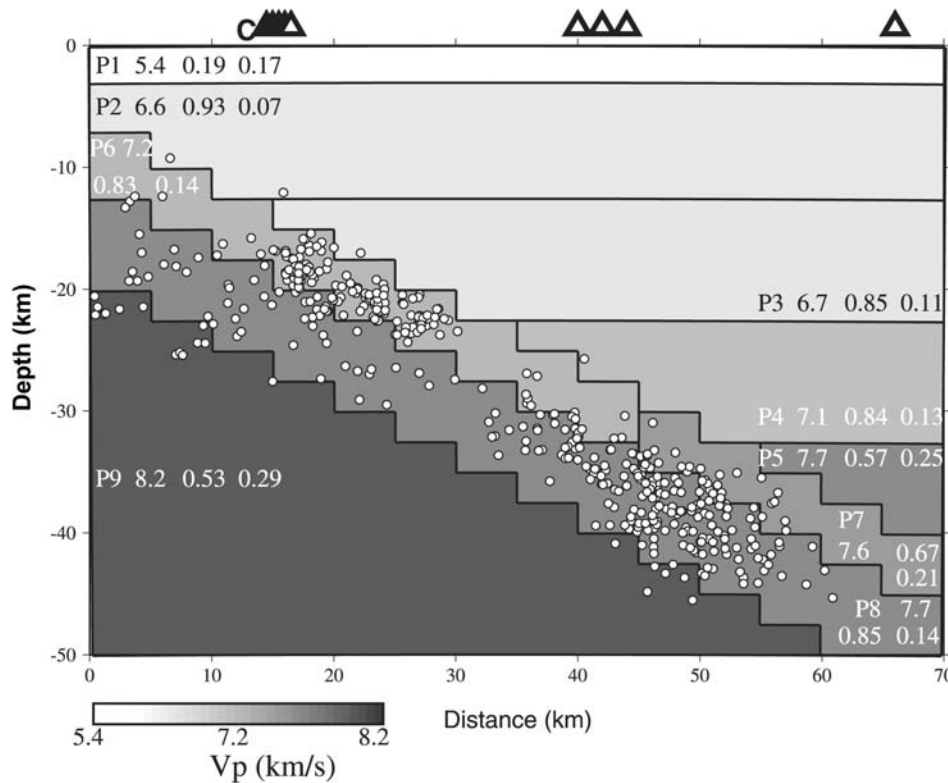


Fig. 7. Relocated seismicity with the final velocity model of the Guerrero gap. Four flat layers P1, P2, P3 and P4 form the continental crust from North America plate, P5 block may represent a mantle wedge. The Moho lies between blocks P4 and P5. The blocks P6 and P7 represent a transitional basaltic zone between Cocos and North America plates. The velocity of P6 suggests the presence of subducted oceanic crust which at a depth of ~30 km is transformed into a higher velocity layer (P7) suggesting a transitional zone. P8 is a transitional layer from upper mantle to oceanic crust. P9 is perhaps the upper mantle.



to sink into the upper mantle. The age of the Cocos plate (Kostoglodov and Bandy, 1995) is of 13.5 Ma in the trench, and 17.0 Ma at the deepest seismicity. Convergence velocity between the Cocos and North America plates is 5.3 cm/yr (Bandy, 1992). A heat flow of  $\sim 135$  mW/m<sup>2</sup> matches the requirements of Kirby *et al.* (1996) to form eclogite at shallow depths within the subducted plate.

Other authors have found a phase change in the upper oceanic crust. In the Pacific plate, Northeast Japan, Hurukawa and Imoto (1992) suggest a phase change from basalt to eclogite controlling the maximum depth of coupling. In the Philippine plate, SW Japan, Hori *et al.* (1985) and Hori, (1990) propose a wave guide layer and a phase change from gabbro to eclogite (12-22 Ma) which reaches a maximum depth of 60 km and a thickness of less than 10 km ( $V_p=7.0$  km/s), though there is no evidences that these changes occur below to 60 km of depth. In Central and North Chile, Comte *et al.* (1994) found a phase change at  $\sim 70$  km of depth.

In the Mexican subduction zone, the seismogenic coupling area has a maximum depth of  $\sim 25$  km depth (Suárez *et al.*, 1990; Pardo and Suárez, 1995; Kostoglodov *et al.*, 1996; Suárez and Sánchez, 1996 and Pacheco *et al.*, 1993). Therefore, velocity differences between blocks P6 and P7 may be responsible for the changes related to the seismogenic coupling zone. The differences between both blocks match with the change in seismotectonic regime between both bands. The first band shows only shallow-thrust faulting mechanisms over the Cocos-North America interface; the second seismic band is mainly within P7 block and shows thrust faulting for shallow seismicity and normal faulting for deep seismicity (Suárez *et al.*, 1990; Araujo, 1991). After relocating the earthquakes, the first band shows an alignment that defines the coupling zone above the P6 block. The second seismicity band presents less dispersion in relation to hypo71 localization. The upper border of this seismicity coincides with the interface between both P6 and P7 blocks (Figure 7), after eclogite formation (Kirby *et al.*, 1996; Figure 7).

The P8 block (Figure 7) seems to match to layer 3 of the oceanic lithosphere as proposed by Spudich and Orcutt (1980) which they defined as having average velocities between 7.2 and 7.8 km/s. This "basal layer" is defined as a transition zone between the crust and the oceanic upper mantle. Clague and Straley (1977) mention that serpentinized peridotite is commonly found to underlie the gabbro unit. Thus P8 block may represent a transitional layer between the Cocos plate (oceanic crust) and the upper mantle. The distribution of blocks of the continental crust, P1 to P4, in our model is in agreement with the continental arc tectonic province proposed by Christensen and Mooney (1995). This province is composed by three flat blocks. The first block has a thickness of 18 km and  $V_p$

interval of 5.7-6.4 km/s, the second block has a thickness of 10 km and  $V_p$  interval of 6.4-6.8 km/s, and the third block has a thickness of 10 km and  $V_p$  interval of 6.8-7.8 km/s. The last block has a thickness of 18 km and a  $V_p$  interval of 5.7-6.4 km/s. Below the continental crust there is an upper mantle block with  $V_p > 7.8$ .

## CONCLUSIONS

A two-dimensional seismic velocity model for Guerrero gap was obtained using a linearized inversion scheme, the damped least square method (Roecker, 1981 and 1982). 6955 micro-earthquakes were used. The proposed model is composed of four flat continental layers with  $V_p$  interval of 5.4 to 7.1 km/s and  $V_s$  (S-wave velocity values) interval of 3.2 to 4.0 km/s. The Moho interface is located at a depth of  $\sim 32$  km on top of the upper continental mantle layer. The oceanic crust dips at an angle of  $\sim 26^\circ$  and is composed of three megablocks. The two shallower blocks reflect the Cocos-North America plate interface and apparently show the presence of a phase change from basalt to eclogite at the bottom of the seismic coupling zone. It was found that seismic velocity of oceanic crust varies from 7.2 to 7.7 km/s for P-wave and 4.0 to 4.2 km/s for S waves. An upper mantle block was defined with 8.2 km/s for P-wave and 4.7 km for S wave.

## ACKNOWLEDGEMENTS

We thank Steve Roecker for providing us his computer programs, Jorge Estrada and Jesús Antonio Pérez for their technical support to the Guerrero telemetric network. Shri Krishna Singh and an anonymous reviewer for their suggestions, comments and corrections to the paper.

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