Geometry and state of stress of the Wadati-Benioff zone in the Gulf of Tehuantepec, Mexico

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[1] Data recorded in the Gulf of Tehuantepec and published moment tensor solutions were used to infer the geometry of the Wadati-Benioff zone (W-B zone) and the stress distribution of the subducted Cocos Plate. From northwest to southeast the subducted slab gently increases its dip, bends up at depths of the order of 100 km and about 240 km inland from the trench, then unbends and increases its dip toward the southeast below Chiapas. Contour lines of equal depth at 50 and 100 km show a significant contortion of the W-B zone west of the Isthmus of Tehuantepec and coincide with significant changes in the topographic features of the crust. We calculated a \( V_p/V_s \) ratio of 1.75 for the whole area and a Moho depth in the Gulf of Tehuantepec of 28.5 ± 3.5 km. Near the trench, along the coupling zone, \( T \) axes of interplate and intraplate earthquakes are oblique to the interface and parallel to the dip direction of the subducted plate, respectively. At depths greater than 50 km the \( T \) axes are roughly horizontal. Best fit stresses using the Gephart and Forsyth [1984] code resulted in the following variation of the minimum stresses (\( T \) axes) from northwest to southeast as (plunge, azimuth) \( s_{3(40^\circ/C_176,37^\circ/C_24)} \) to \( s_{3(28^\circ/C_176,72^\circ/C_24)} \), then to \( s_{3(11^\circ/C_176,54^\circ/C_24)} \) and finally to \( s_{3(27^\circ/C_176,35^\circ/C_24)} \).

We also analyzed recordings from the 30 September 1999, Oaxaca earthquake \( M_w = 7.5 \) and its aftershocks. We inferred an approximate fault area of 80 by 30 km inside the subducted Cocos Plate.

INDEX TERMS: 7203 Seismology: Body wave propagation; 7205 Seismology: Continental crust; 7230 Seismology: Seismicity and seismotectonics; KEYWORDS: seismicity, Wadati-Benioff zone, stress distribution


1. Introduction

[2] The convergence of the Tehuantepec Ridge (TR) between Oaxaca and Chiapas has produced a complex pattern of deformation in the continental crust as well as in the subducted lithosphere, and consequently, it has generated a high rate of seismic activity in the whole area. West of the TR the dip of the subducted plate is \( \sim 20^\circ \), and hypocenters of the earthquakes are no deeper than 100 km [Pardo and Suarez, 1995]. On the other hand, east of the TR the subducted slab deepens at an angle of \( 40^\circ \), and the hypocenters can reach depths of the order of 270 km [LeFevre and McNally, 1985; Rebollar et al., 1999a, 1999b]. This zone has been proposed as a seismic gap [Kelleher et al., 1973; McCann et al., 1979; Singh et al., 1981; McNally and Minster, 1981; Astiz et al., 1988].

LeFevre and McNally [1985] suggested an aseismic subduction of the TR. Figure 1 shows the location of the TR and the controversial location of the Tehuantepec gap. Ponce et al. [1992] carried out a seismic study in this area, and they found that the dip of the subducted slab occurred gradually over a length of 150 km parallel to the trench from west to east; however, they reached that conclusion using a limited data set.

[3] In this study, we used data from a network of 13 analog stations deployed in Oaxaca and Chiapas that span a large period of recording. This network has been operated since January 1999 up to now by the Departamento de Sismotectonica de la Comision Federal de Electricidad (CFE). In this study, we report the analysis of the seismic activity recorded from January 1999 to September 2002, and we infer the geometry of the Wadati-Benioff (W-B) zone, the depth of the crust using the converted S-to-P phases (\( S_p \)), and from published moment tensor solutions (MTS) the stress orientations on the subducted Cocos Plate.
in the Tehuantepec Ridge. We also report the aftershocks of the intraplate Oaxaca normal earthquake of 30 September 1999 $M_w = 7.5$ magnitude event.

2. Tectonic Setting

[4] In the area under investigation the Cocos (CO), Caribbean (CA), and North American (NA) Plates (Figure 1) converge. The oceanic Cocos Plate subducts beneath North American and the Caribbean Plates which give origin to the Middle American Trench (MAT). The motion between the Caribbean and the North American Plates takes place along the Motagua-Polochic Fault Zone (MOFZ), a large sinister strike-slip fault. The CO Plate moves at a rate of $\sim 7.1$ cm/yr in the northeast direction, the NA Plate moves in a west-southwest direction at a rate of $\sim 3.0$ cm/yr, and the CA Plate moves with an approximately northeast direction with a relative velocity of $\sim 1.9$ cm/yr from the MAT [DeMets et al., 1990].

[5] The Cocos Plate varies in age roughly from west to east at the same time that it subducts the MAT in increasing rates from northwest ($\sim 4.8$ cm/yr) to southeast ($\sim 7.5$ cm/yr) [DeMets et al., 1990]. The Cocos Plate has fractures zones, and the Tehuantepec Ridge (TR) converges toward the MAT. As the TR converges to the MAT, it has a great influence in the way the Cocos Plate subducts in this region (Figure 1). Younger age crust subducts at a shallow dip angle north-northeast of the TR that contrasts with subducted crust with a steep angle and older crust of about 10 to 25 Myr southeast of the TR [Couch and Woodcock, 1981; Rebollar et al., 1999a].

[6] West of the TR a stronger coupled plate interface has been interpreted on the basis of the occurrence of large thrust interplate earthquakes [Singh and Mortera, 1991; Pardo and Suarez, 1995]. The region east of the TR has been interpreted as a seismic gap [Kelleher et al., 1973; McCann et al., 1979; Singh et al., 1981; McNally and Minster, 1981; Astiz et al., 1988]; however, the existence of this gap is controversial because in this area have occurred medium sized earthquakes (R. Madariaga, personal communication, December 2002). Pardo and Suarez [1995] have observed a maximum downdip depth of $\sim 25$ km that is subhorizontal, west of the TR, while Ponce et al. [1992] inferred the Wadati-Benioff (W-B) zone with a dip in the range of 45° to 50° in the TR. On the other hand, Rebollar et al. [1999a] estimated a W-B zone $\sim 39$ km thick dipping $\sim 40°$ southeast of the TR.

[7] The continental crust in this area is characterized by different “tectonostratigraphic” terrenes, which ideally correspond to geologic blocks with a coherent stratigraphic sequence and bounded by major tectonic subvertical discontinuities [Campa and Coney, 1983; Sedlock et al., 1993]. However, their location, boundaries, kinematics, and structure at depth are still under controversy. Nevertheless, in the Oaxaca region, gravity modeling shows that the crust is $\sim 40$ km thick with a density consistent with continental affinity [Arzate et al., 1993].

[8] Some paleostress analysis in conjunction with geological observations has been carried out in order to define the continental stress regime in the continental portion of the Isthmus of Tehuantepec during the Mesozoic and Tertiary [Barrier et al., 1998; Guzman-Speziale and Meneses-Rocha, 2000]. There it has been proposed a tensional regime in southern Mexico for the last $\sim 6$ Myr as a consequence of the deformation produced by the subduction of the Cocos Plate and the eastward displacement of the western portion of the Cocos Plate.
of the Caribbean Plate. This extensional regime has been associated with the development of both the Motagua-Polochic Fault Zone and the evolution of the passive margin of the Gulf of Mexico.

3. Historical Seismicity

[9] Table 1 shows coordinates of large events (greater than 7) that occurred during the last century between 96°W and 92°W and reported by different authors. Figure 1 shows the location of the events. The proposed seismic gap in the Gulf of Tehuantepec between 95.3°W and 94°W is also depicted. Indeed, the last earthquake greater than 7.0 that occurred in this area was in 1941 (see Table 1).

4. Data Recording

[10] We deployed a network of thirteen portable analog seismic stations in Oaxaca and Chiapas since 1999 as well as a strong motion digital station. Figure 1 shows the location of the seismic stations. The deployment and operation of this network has been logistically difficult because of the analog recording and the topographic features of this region. However, we were able to maintain the network in a good health status. The stations consist of MQ800 Sprengnether analog smoke paper data recorders connected to 1 s Mark velocity seismometers. An operator synchronized the internal clock of the MQ800 every day. However, sometimes the internal clock was not synchronized. In that case we calculated the correction of the internal clock by doing a linear interpolation between the last two times that the station was synchronized with the WWVB ratio time signal. The velocity of the recording drum was 120 cm/mm. This kind of continuous analog recording, even cumbersome, is ideal to record all arrivals of P and SV waves of small to medium size magnitude earthquakes. In order to have a good control in the location of the activity in the Gulf of Tehuantepec, four stations were deployed in a small aperture array. Maximum analog reading errors of P and S waves are of the order of 0.1 and 0.2 s, respectively.

5. Event Locations and $V_p/V_s$ Estimate

[11] Earthquakes were located using HYPO71 computer code [Lee and Lahr, 1972]. The crustal one-dimensional (1-D) P wave velocity model estimated by Váldes et al. [1986] was used to locate the earthquakes. We calculated S wave velocity using a $V_p/V_s$ ratio of 1.75 (later estimated). We located earthquakes recorded at least in four stations with 6 or more phases that included at least two S waves picks. We started to locate earthquakes with trial depths of 25, 50, 75, and 100 km. We compared HYPO71 outputs and we selected events with root mean square error of time residuals (RMS) of less than 1 s and with standard error of the epicenter (ERH) and standard error of the focal depth (ERZ) of less than 15 km. From the thousands of earthquake recorded, 1897 fulfilled the aforementioned criteria. Figure 2 shows the earthquake locations. It is well known that focal depths are well constrained when we have stations close to the epicenter. Therefore we selected events with nearly vertical source-station paths (80% of the events fulfill this criterion). We found a cluster of seismic activity north of the intersection of the TR and the MAT (square 1 of Figure 2a). There are 103 events located in the square 1. On the other hand, in the adjacent square 2 in Figure 2a only 21 events were located. Therefore we think that there is a vacancy of activity in this area.

[12] In order to calculate $V_p/V_s$ ratios we proceeded in the following manner. First, we plotted $S$-P times versus P waves arrival times and calculated origin times by a linear least squares algorithm. We considered events with a correlation coefficient of 0.95. Then, we plotted $T_p-T_p$ versus $T_p-T_0$ times, where $T_p$ and $T_0$ are the P and S travel times and $T_0$ is the origin time. A line was fitted through the origin up to 40 s that included 95% of our P and S wave
picks. An average $V_p/V_s$ ratio of 1.75 was obtained (see Figure 3). Following Riznichenko [1958] and Nicholson and Simpson [1985], we calculated average $P$ wave velocities as a function of depth, and with the already calculated $V_p/V_s$ we estimated the $S$ wave velocities as a function of depth. Figure 3 shows $P$ and $S$ wave velocities as a function of depth, where we can see a monotonically increase of velocities with depth (Figure 3).
Two large earthquakes were recorded by our network, the Puebla earthquake on 15 June 1999 $M_w = 7.0$ [Yamamoto et al., 2002] and the Oaxaca earthquake on 30 September 1999 $M_w = 7.5$. The Puebla earthquake is out of the area of influence of our network; however, the Oaxaca earthquake lies inside our network, and we were able to locate its aftershocks. A star on Figure 2 depicts the location of the main event, and a profile perpendicular to the trench is also shown in Figure 2.


Inspection of the seismograms recorded in the seismic stations, and displayed in the square of Figure 4, showed clear converted $Sp$ phases at the Moho. Figure 5a shows examples of the events with converted $Sp$ phases. Sixteen events were selected. Figure 5b shows an example of its trajectories in a cross section from the source to the HUA station.

We calculated the Moho depth by minimizing observed and calculated travel times in an iterative process. Figure 5b shows a vertical profile with the hypocenter of the earthquakes with $Sp$ phases. Therefore, in order to calculate the $P$ and $S$ travel times we considered a layer

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**Figure 3.** $V_p/V_s$ and average $P$ and $S$ wave velocities as a function of depth calculated with the Wadati and Riznichenko techniques. Light grey lines are the $P$ and $S$ wave velocities as a function of depth.

**Figure 4.** Map showing the location of the events with $Sp$ converted phase at the Moho discontinuity. Triangles are the seismic stations.
Figure 5. (a) Examples of seismograms of events that occurred in the subducted plate that show clear converted $Sp$ phase at the Moho. Sixteen events were selected. (b) Cross section of the selected events with $Sp$ phases recorded at HUA station as well as the parameters used in the estimate of the Moho depth. Number is their identification.
the thickness of the crust, the average velocity of the upper mantle (Moho depth of the order of 28.5 ± 3.5 km). From the variations of the RMS residuals we estimated a variations of the RMS residuals for different Moho depths. Where \( \text{RMS} \) and Riznichenko diagram (Figure 3) we calculated a in each of the layers (crust and mantle). From the Wadati and transmitted rays, so we have

\[
\frac{V_2}{\Delta_1} - \frac{(\Delta - \Delta_1)}{(\Delta_1 + H_1)^{1/2}} = 0, \tag{1}
\]

where \( V_1 \) is the average velocity of the crust \((P\ or\ S)\), \( V_2 \) is the average velocity of the upper mantle \((P\ or\ S)\), \( H_1 \) is the thickness of the crust, \( H \) is the focal depth, \( \Delta_1 \) is the horizontal distance between the seismic station and the vertical projection to the surface of the transmitted P-to-S phase in the Moho, and \( \Delta \) is the epicentral distance (see Figure 5b). Numerically solving equation (1), we obtained \( \Delta_1 \). Then we calculated \( P \) and \( S \) wave travel time’s \( t_p \) and \( t_s \) in each of the layers (crust and mantle). From the Wadati and Riznichenko diagram (Figure 3) we calculated a \( V_{p1} = 6.2 \text{ km/s} \) and a \( V_{p2} = 8.3 \text{ km/s} \), and from the \( V_{p1}/V_{s1} = 1.76 \) and \( V_{p2}/V_{s2} = 1.73 \) we calculated S wave velocities. Travel times were calculated by varying the Moho depths from 5 to 60 km. Once travel times were calculated, we computed

\[
\text{RMS} = \sqrt{[t_p - t_{p1}]^2 + [t_s - t_{s1}]^2 + [t_p - t_{p2}]^2 + [t_s - t_{s2}]^2 + \cdots}
\]

residuals for different Moho depths. Where \( (t_p-t_{p}), (t_s-t_{s}), \) is the \( P \) minus \( S \) observed travel time and \( (t_p-t_{p}), (t_s-t_{s}), \) is the \( P \) minus \( S \) calculated travel time and so on. Figure 6 shows the variations of the RMS residuals for different Moho depths. From the variations of the RMS residuals we estimated a Moho depth of the order of 28.5 ± 3.5 km.

7. Aftershocks of the 30 September 1999 Event

[16] We recorded the 30 September 1999 Oaxaca event and its aftershocks up to June 2000, when we recorded a magnitude 4.6 event that occurred at a depth of 50 km. Source mechanisms of the main event and five aftershocks indicate that the intraplate events were normal fault with the strike parallel to the trench and dipping to the north-northeast [Singh et al., 2000; Hernandez et al., 2001]. Hernandez et al. [2001] found that the slip was mainly released at a depth of 45 km inside the subducted Cocos Plate. The depths of the hypocenters range from 12 to 50 km. Figure 2c shows a cross section perpendicular to the Middle America Trench where we show the location of the main event. From Figure 2c it can be seen that the aftershocks occurred updip of the main event. The preferred fault plane, taken from Hernandez et al. [2001], is depicted in Figure 2c as well as the Cocos-North America interface.

8. Shape of the Wadati-Benioff Zone and Stress Distribution of the Subducted Lithosphere

[17] In order to investigate the shape of the Wadati-Benioff zone we constructed a mesh of 12 by 13 circles with a diameter of 30 km that cover the whole area of study (Figure 7). Within each circle we choose events from our catalog with standard error of the focal depth (ERZ) of less than 10 km. We calculated the mode [Mood and Graybill, 1963, p. 107] of the focal depth with the selected events on each circle. With this criterion we were able to find the mode of 83 points (black circles in Figure 7). White circles in Figure 7 are areas were it was not possible to define the mode. Figure 8 shows vertical cross sections perpendicular (A–L) and parallel (1–13) to the MAT. Open circles are the events, and open squares are the mode focal depths that define the W-B zone. From the cross sections perpendicular to the trench we can see that the dip of the W-B zone gently increases from east to west. Cross sections E-H are the best defined and suggest that the subducted lithosphere increases its dip and bends up at about a depth of 100 km. Farther southeast the subducted slab unbends and increases its dip. A 2-D contour surface of the W-B zone was calculated...
using Surfer 8 [Golden Software, Inc., 2002] code that uses the Kriging gridding method. Figure 9 shows contour lines of equal depth of the subducted Cocos Plate at 10 km intervals. Contour labels were placed on contour lines of 50, 100, and 150 km. The contour lines of 50 and 100 km converge west of the Isthmus of Tehuantepec and correspond to the E, F, and G cross sections. It can be observed that cross section F has shallow and low-magnitude ($M < 4$) seismic activity in the continental crust. Ponce et al. [1992] also reported this pattern of shallow seismic activity. We think that this nest of seismic activity could be linked to the bend of the MAT to the east. From Figure 9 it can be seen that there are significant changes in the topographic features in the crust in the contortion of the W-B zone. The MAT lies to the west of this area, and a wide continental shelf lies to the east. The hachured area is the coupled zone between the subducted Cocos Plate and the overriding North American Plate defined up to a depth of 40 km. However, from the

**Figure 8.** Vertical cross section of seismicity projected perpendicular (A–L) and parallel (1–13) from the Middle America trench. Numbers in the top of the plots are centered in the circles of Figure 7. Open circles are the events, and open squares are the mode. Description of the seismicity is given in the text.
analysis of the seismicity it can be seen that the coupled zone is not uniform in this region.

[18] Cross sections (30 km wide) parallel and oblique to the trench, following the coast, were plotted in order to see roughly the coupled zone of the Cocos Plate and the overriding North American Plate from east to west along the Gulf of Tehuantepec (see Figure 10). Profile ABDD’ shows the coupled zone and depth extent of the seismic activity. It also shows a pocket of activity in the neighborhood of point C. This area coincides with topographic features and the closeness of the lines of 50 and 100 km contour lines of the W-B zone. Roughly, half the way between C and C’, there is a small group of events. In this zone, Nuñez-Cornu and Ponce [1989] proposed the location of the 1917 magnitude 7.7 event (Table 1). Pardo and Suárez [1995] also reported thrust events in this area that coincides with the projection of the Tehuantepec Ridge under the North American Plate.

[19] Profile ABDE shows features similar to the former profile; however, in the neighborhood of point D the activity migrates to depths of the order of 50 km. In this zone a normal event of magnitude 6.7 occurred at a depth of 60 km [González-Ruiz, 1986]. Figure 10 shows the location of the event as well as the strike and dip of one fault plane of the reported fault plane solution. The gently increase of the activity with depth suggests that the Cocos Plate started to bend down dip because we moved away from the MAT. Profile ABEE’ follows the coastline of the Isthmus of Tehuantepec. Near point E we can see a shallow pocket of activity with events with magnitudes smaller than 4. Ponce et al. [1992] reported this zone of shallow seismic activity. Also near this point the W-B zone starts to bend down dip, and the activity along the coast follows the W-B contour line of 100 km.

[20] Now, it is possible to have access to moment tensor solutions (MTS) from the U.S. Geological Survey (USGS) Web page (http://eqint.cr.usgs.gov/neic/), which includes Harvard and preliminary determination of epicenters (PDE) moment tensor solutions. We went though that catalog and searched for MTS of events located in the Isthmus of Tehuantepec. We found 123 MTS with magnitudes greater than 5.0 since 1977. In our analysis we included the 30 September 1999 (Mw = 7.5) Oaxaca earthquake and five of its aftershocks [Singh et al., 2000]. Fault plane solutions reported by Rebollar et al. [1999a] in Chiapas and the 30 January 2002 (Mw = 5.9) Veracruz earthquake was also included. We applied the Gephart and Forsyth [1984] and Gephart [1990] inversion code in order to invert for the best fit P and T axes along the downgoing subducted plate.

[21] As a mean of visualizing variations of P and T stress vectors along the subducted lithosphere, we plotted cross sections A, C, E, and G described in Figure 7. All cross sections started at the trench. Figure 11 shows cross sections that included T axes projections along the strike of the profiles, and Figure 12 shows plots of P and T axes on an equal-area lower projection. Profile A (Figure 11a) shows projections of T axes before the MAT started to bend to the east. Near the trench along the coupling zone, T axes of interplate earthquakes are oblique to the interface (P axes normal to the interface of the overriding and subducted slab), while T axes of intraplate events lie along the dip direction of the subducted plate, which means that below the coupling zone, the slab is mainly under tension (slab-pull events). At depths greater than 50 km, T axes are mainly horizontal, indicating that the slab is rupturing along the dip direction or with steeply dipping angles. Best fit stresses ($\sigma_1 > \sigma_2 > \sigma_3$) obtained from the inversion of P and T axes along this profile are (plunge, azimuth) $\sigma_1 (50^\circ, 220^\circ)$ and $\sigma_3 (40^\circ, 37^\circ)$ (Figure 12a). Profile C (Figure 11b) included events from the area where the trench starts to bend from northwest to east. Again we observed the same features as before for interplate events; however, there are few intraplate slab-pull events with T axes along the dip direction. There are less T axes at depths greater than 100 km; however, they indicate that the slab is under tension. Best fit stresses are $\sigma_1 (44^\circ, 193^\circ)$ and $\sigma_3 (28^\circ, 72^\circ)$ (see Figure 12b). Along E profile (Figure 11c) the MAT started to follow its original strike toward the southeast where the continental shelf starts to widen. T axes along the coupling zone are no longer oblique, and T and P axes orientations are complex along the coupling zone; however, intraplate events indicate that the slab is under tension. At depths greater than 100 km the subducted plate is dominated by slab-pull events. Best fit stresses are $\sigma_1 (62^\circ, 165^\circ)$ and $\sigma_3 (11^\circ, 54^\circ)$ (Figure 12c). Finally, G profile (Figure 11d) had more MTS that the previous profiles, and the dip of the W-B increases to $\sim 40^\circ$. The strikes of the T axes of interplate events are oblique to the coupling zone with a few exceptions. There are intraplate events that indicate that the subducted plate is under tension. T axes of deeper events
Figure 10. (top) Map showing lines parallel and oblique to the trench that we chose to project in cross sections the seismic activity (light white lines). Dashed line shows the location of the MAT. (bottom) Projection of the seismic activity in cross sections parallel and oblique to the MAT. White circles are the shallow events, and black circles are deeper events. Star shows the location of the event of magnitude 6.7 reported by González-Ruiz [1986] and its possible fault plane.
Figure 11.
indicate that the subducted slab in under tension; however, there is one event that indicate that the subducted slab in under compression (slab-push event). The best fit stresses of this profile are $\sigma_1(63^\circ, 200^\circ)$ and $\sigma_3(27^\circ, 35^\circ)$ (Figure 12d).

9. Summary and Conclusions

We have analyzed the seismic activity recorded in a network of analog seismic stations deployed in Oaxaca and Chiapas that encompass the Isthmus of Tehuantepec. We used the USGS catalog of moment tensor solution to have an insight of the stress orientations within the subducted plate in this area, and we used 1897 events to infer the geometry of the W-B zone. To obtain principal stress orientations ($P$ and $T$ axes), we used MTS compiled by the USGS and fault plane solution reported by Rebollar et al. [1999a] and Singh et al. [2000]. Duration magnitudes of the events recorded in our network varied from 1.8 to 4.2. We calculated a $V_p/V_s$ of 1.75 that within the errors represents a Poisson solid. Within the time window of observation we recorded the Oaxaca normal fault earthquake of 30 September 1999 ($M_w = 7.5$) and its aftershocks.

Figure 11. Projections of $T$ axes in cross sections (depth versus distance) from northeast to southeast that were obtained from the USGS catalog, Rebollar et al. [1999a], and Singh et al. [2000]. (a) $T$ axes of the cross section of lines A and B of Figure 7. (b) $T$ axes of the cross section of lines C and D of Figure 7. (c) Cross section of lines E and F of Figure 7. (d) Cross section of lines F and G of Figure 7. Arrows are the projection of the $T$ axes along the cross section. Circled arrows at the right are the best fit $T$ axes of stresses obtained with the Gephart and Forsyth [1984] and Gephart [1990] inversion code. Upper left and right coordinates are the points where cross sections were projected. Plotted with the Louvari and Kiratzi [1997] program.

Figure 12. A lower hemisphere Schmidt stereonet showing $P$ (solid circle) and $T$ (open circle) axes from the cross sections of Figure 11. Large circles are the best fit stress orientation obtained with the inversion process. Plotted with the Louvari and Kiratzi [1997] program.
The aftershocks were located at depths that varied from 20 to 50 km, and from its locations we inferred a fault area with a length of 80 km along the strike of the trench and 30 km wide along the dip direction of the subducted plate.

[23] We plotted seismic cross sections from northwest to southeast perpendicular from the MAT (profiles A–L) and parallel (profiles 1–13) from the MAT in order to see the geometry of the W-B zone. Profiles A and B (Figure 8) show that there is a vacancy of events at depth at about 50 km that extends between about 60 and 120 km from the trench. There is also a vacancy of seismic activity, observed in profiles C and D, in the depth range from 100 km up to 180 km and about 300 km from the trench. LeFevre and McNally [1985] also observed this vacancy of seismicity. Profiles E, F, G, and H do not show any gap of events along the downgoing slab. However, these profiles suggest that the subducted slab becomes buoyant and flattens up. Profiles I and J show that the subducted slab loses its buoyancy and the dip of the W-B zone started to increase. From these cross sections it is evident that the lateral variations in the dip angle of the subducted slab are from northwest to southeast.

[24] Figure 10 shows profiles 30 km wide parallel and oblique to the MAT. Those profiles clearly show the seismogenic zone of the subducted slab along the strike of the MAT. The activity is mainly concentrated up to depths of 50 km along the strike; however, depths of the events started to increase between points C and D (see Figure 10) since the lithosphere started to bend down and because we are not able to locate events in this coupling zone of the subducted and overriding plate. In this area of the subducted plate, Nuñez-Cornu and Ponce [1989] proposed the location of the 1917 magnitude 7.7 earthquake and González-Ruiz [1986] located an earthquake of magnitude 6.7. As we go farther southeast, the depths of the events seems to increase to about 100 km because we can not locate events below the continental shelf with enough precision. The inversion of the $P$ and $T$ axes, using the Gephart and Forsyth [1984] and Gephart [1990] technique, indicate that the best fit $T$ axes ($\sigma_{T}$plunge, azimuth)) varied from northwest to southeast like $\sigma_{T}(40^\circ, 37^\circ)$ to $\sigma_{T}(28^\circ, 72^\circ)$, to $\sigma_{T}(11^\circ, 54^\circ)$ and finally to $\sigma_{T}(27^\circ, 35^\circ)$.

[25] The observed stress pattern in this study has been inferred in Oaxaca with the intraplate normal fault 1931, magnitude 7.8 earthquake, the thrust fault interplate 1978, magnitude 7.6 earthquake and again the normal fault intraplate 1999, magnitude 7.5 earthquake [Singh et al., 1985, 2000]. Farther northwest in the geographic limits of Michoacan and Guerrero, the 1985 interplate thrust fault, magnitude 8.1, earthquake and the 1997 intraplate normal fault earthquake follows the same pattern. Mikumo et al. [1999] suggested that the 1985 thrust fault earthquake transferred enough stresses inside the subducted plate so that it triggered the normal 1997 intraplate earthquake. We observed the same pattern in our area of study; compressional events (thrust faulting) in the interplate coupled zone of the subducted and overriding plates and intraplate slab-pull (extensional) events below coupled zone. LeFevre and McNally [1985] found out the same stress distribution on the subducted slab in the Gulf of Tehuantepec. Lemoine et al. [2002] studying intermediate depth slab-pull and slab-pull intraplate earthquakes in Mexico, Peru, and north central Chile suggested that the slab-pull intraplate events and slab-pull intraplate events can be explained as due to flexure of the downgoing slab.

[26] In conclusion, we were able to infer the geometry of the W-B zone. We also clearly observed lateral variations in the dip of the W-B zone from northwest to southeast. It was observed a shallow dip below Oaxaca that smoothly increases toward Chiapas to an angle of 40°. However, during this transition we observed a contortion of the subducted slab, clearly seen in the depth contour lines of 50 and 100 km northwest of the intersection of the Tehuantepec Ridge and the MAT. This zone coincides with the region where Sierra Madre Occidental ends and starts the Chiapas continental shelf. Using travel times of converted $S$ to $P$ ($S_{p}$) phases at the Moho, we were able to calculate the thickness of the continental crust. We estimated a thickness of 28.5 ± 3.5 km in the Gulf of Tehuantepec. $T$ and $P$ axes show that the interplate interface is under compression and that the plate below the coupled zone is under tension. As Lemoine et al. [2002] pointed out, slab-pull intraplate events are rare; however, one slab-pull intraplate event is observed in cross section of Figure 11b, and Rebollar et al. [1999a] reported one slab-pull intraplate event at the end of the subducted slab of Figure 11d.

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