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The Milpa Alta earthquake of January 21, 1995

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RESUMEN

Durante el último año se produjo un incremento significativo en el número de estaciones sísmicas en operación en el Valle de México. Además, como respuesta al reciente incremento en la actividad fumarólica y sísmica en el volcán Popocatépetl, una densa red sísmica de seis estaciones se instaló alrededor de dicho volcán. Es por ello que el reciente evento del 21 de enero de 1995 (M_c = 3.9), localizado cerca de la población de Milpa Alta, a una profundidad de 12 km, es el evento mejor registrado dentro de la Faja Volcánica Trans-Mexicana. El análisis de este temblor se facilitó con el uso de dos sismógrafos de banda ancha, uno en Ciudad Universitaria (CU), y el otro cerca de Tlamacas: ambos registraron el sismo. Para restringir el mecanismo focal, desarrollamos un algoritmo que utiliza datos de primeros arribos, polaridades de las fases SV_z y SH, y las razones de amplitud P_z/SH y SV_z/SH, medidas en los registros de desplazamiento en las estaciones de banda ancha. El mecanismo focal (rumbo 106°, buzamiento 63°, corrimiento -39°) corresponde a un fallamiento normal con una gran componente lateral (50%). Este mecanismo es muy similar al mecanismo compuesto determinado a partir de las réplicas del evento del 7 de febrero de 1984 (M_c = 3.9), ocurrido en el poblado cercano de Juchitepec. El eje T de estos dos eventos está orientado NS, en concordancia con la orientación de esfuerzos inferidos del alineamiento de conos volcánicos cineríticos. Este régimen de esfuerzos tensional en la región puede deberse a la elevación del altiplano y/o a un retroceso de la trinchera.

PALABRAS CLAVE: Sismo, Faja Volcánica Trans-Mexicana.

ABSTRACT

In the past year there has been a significant increase in the number of seismic stations operating in the Valley of Mexico. Also, a dense network of six stations is in place around the Popocatépetl volcano, in response to the recent increase in seismic and fumarolic activity. For this reason, the recent earthquake of January 21, 1995 (M_c = 3.9), located near the town of Milpa Alta, at a depth of about 12 km, is the best recorded event in the Trans-Mexican Volcanic Belt. The analysis of this earthquake was facilitated by two broadband seismographs, one in Ciudad Universitaria (CU) and the other near Tlamacas, both of which recorded this event. To constrain the focal mechanism we developed an algorithm which uses first-motion data, polarities of SV_z and SH phase, and P_z/SH and SV_z/SH ratios measured on displacement broadband seismograms. The focal mechanism corresponds to a normal-faulting event with significant (50%) strike-slip component (azimuth 106°, dip 63°, rake -39°). This mechanism is nearly identical to the composite focal mechanism of the aftershocks of February 7, 1984 (M_c = 3.9) earthquake, which occurred in the nearby town of Juchitepec. The T-axes of the two events are oriented NS, in agreement with the stress orientation inferred from the alignment of the cinder cones in the region. This extensional stress regime in the region may be due to the elevation of the altiplano and/or due to seaward migration of the trench.

KEY WORDS: Earthquake, Trans-Mexican Volcanic Belt.

INTRODUCTION

Some features of the Trans-Mexican Volcanic Belt (TMVB) are anomalous and their explanation remains controversial. For example: (a) the orientation of the TMVB is not parallel to the trench (see Figure 1), (b) there is a lack of intermediate-depth earthquakes under the TMVB at least between Chapala and Veracruz (see, e.g., Burbach *et al.*, 1984; Singh and Mortera, 1991; Pardo and Suárez, 1995), and (c) the geological evidence suggests that the stress regime in the TMVB is transtensional (e.g., Mooser, 1972, Shurbet and Cebull, 1984; Suter, 1991; Suter *et al.*, 1992a,b). Although there is a general agreement that the TMVB is linked to the subduction of the Rivera and Cocos plates below Mexico, the consensus is not universal because of the anomalous characteristics mentioned above. An alternative model has been proposed, in which the TMVB is the surface expression of motion along an extensional plate boundary between southern and northern Mexico (e.g., Shurbet and Cebull, 1984). A recent geochemical and isotopic study suggests that rifting, in addition to subduction, is responsible for the mafic magmas in the central TMVB (Verma, 1995).

Recent seismicity studies, based on relocated events and, in some cases, the depths constrained by waveform modelling, show that the dip of the subducted plate varies along the Mexican subduction zone (e.g., Burbach *et al.*, 1984; Singh and Mortera, 1991; Pardo and Suárez, 1995), thus providing a convincing explanation for (a) above. Although no intermediate-depth seismicity has been recorded in the TMVB between Chapala and Veracruz, it is possible that the subducted plate is situated about 100 km below the active volcanoes in the region, as is the case under Jalisco where subduction of the Rivera plate is taking place (Pardo and Suárez, 1993). Perhaps, small intermediate-depth events do occur below the TMVB, but have not been detected because of sparse distribution and poor quality of the seismographic stations.

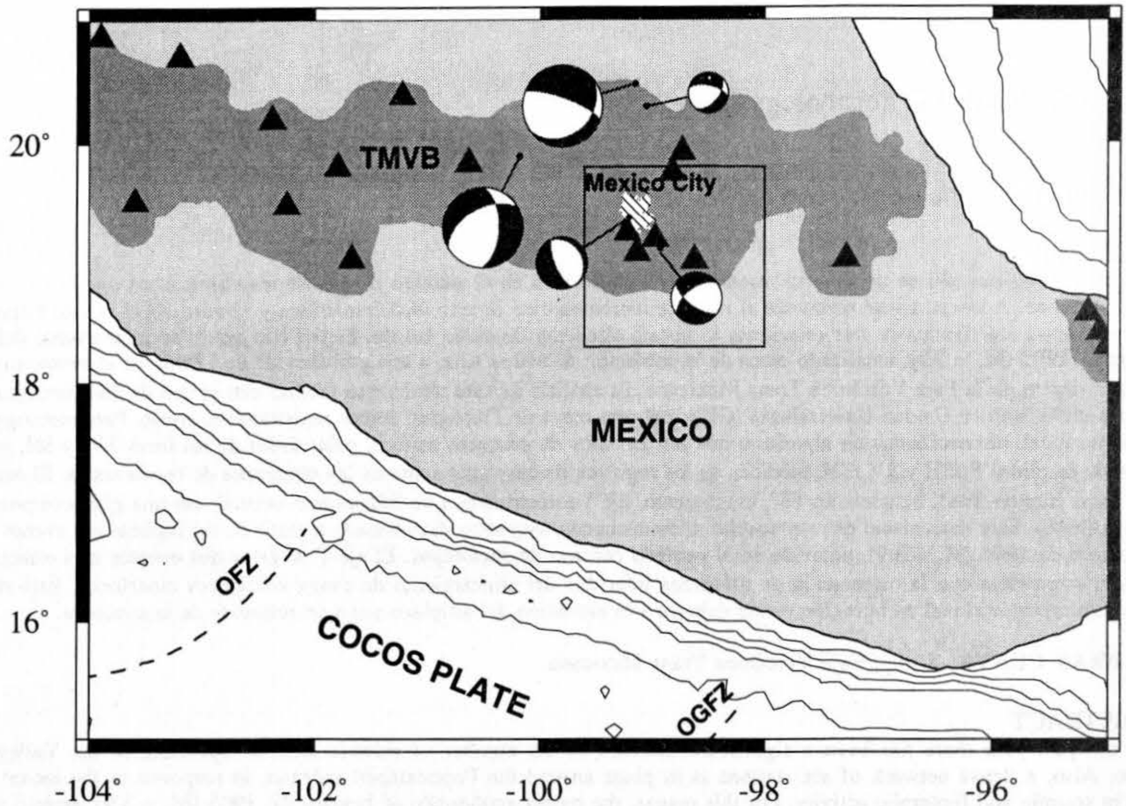

Fig. 1. Map of southern Mexico. Dark area denotes the Trans-Mexican Volcanic Belt (TMVB). Quaternary volcanism is indicated by triangles. The large square area depicts the area on Figure 2. Stippled pattern indicates the City of Mexico. Focal mechanisms correspond to Table 1.

Feature (c) above is mostly based on studies of surface geology, drillhole elongations, alignment of quarternary cinder cones, and striations of active faults. These studies show normal faults with some strike-slip component, which are oriented along the axis of the TMVB, with horizontal minimum stress (S_{Hmin}) perpendicular to the TMVB. This is surprising since, generally, strike-slip faulting is found landward of the trench near active volcanoes, whereas normal faulting is expected beyond the volcanoes, especially in regions where back-arc spreading may be occurring (*e.g.*, Nakamura and Uyeda, 1980). Topographic elevation of the altiplano has been cited as the cause of this extensional stress regime (e.g., Suter, 1991). The expected and observed S_{Hmin} direction produced by high elevations, however, is perpendicular to the direction of convergence (Zoback *et al.*, 1989). Singh and Pardo (1993) present evidence that the entire overriding plate is in extension and suggest a seaward retreat of the middle America trench as a possible mechanism.

Shallow moderate and large earthquakes in the TMVB are relatively infrequent but do occur. The largest instrumental magnitude of such an event is 7.0, for the Acambay earthquake of November 19, 1912 (Urbina and Camacho, 1913). As seismic networks have been relatively sparse in the TMVB, the locations of small and moderate earthquakes have been poor and focal mechanisms are available for only a few events (Figure 1, Table 1). Although the density of seismic stations has been higher in and around the Valley of Mexico since the installation of SISMEX in the mid-seventies, the shallow nature of the seismicity and the complex upper crustal structure have been obstacles to reliable hypocentral determinations.

To resolve some of the tectonic issues raised above and to monitor local activity, installation of new seismic stations began in 1993. The number of stations in the Valley of Mexico has now increased by 6. In addition, 6 new stations have been installed near Popocatépetl volcano to monitor the recent increase in its activity. It is for this reason that the event of January 21, 1995 (M_C=3.9) is probably the best recorded local earthquake in the TMVB. Here we present results from the analysis of this event and discuss them in the tectonic framework of the TMVB.

DATA AND ANALYSIS

Figure 2 is a map of the Valley of Mexico and surrounding areas, including the volcanoes Iztaccíhuatl and Popocatépetl. The figure shows the seismic stations used in the study. Note that except for the broadband stations of CUIG and PPM, the rest are equipped with short-period (1hz), vertical seismometers. The signal from the short-period network is transmitted by radio telemetry to UNAM.

Table 1

List of earthquakes

Date	Latitude (°N)	Longitude (°W)	Depth (km)	Magnitude	Strike (°)	Dip (°)	Rake (°)
761004	20.48	99.15	9.0	5.3[1]	290	75	-66[2]
790222	19.89	100.18	8.0	5.3[1]	240	51	-44[3]
					280	66	-47[4]
810204-15*	19.38	99.20	1.2	3.0-3.4[5]	322	22	-104[5]
840207	19.12	98.92	5.0	3.6[6]	233	57	-149[7]
880602	20.29	99.05	6.0	2.7[8]	282	61	-50[8]
950121	19.18	98.97	12.5	3.9[9]	217	56	-146[9]

[1] International Seismological Center Bulletin.
[2] Suárez and Ponce (1986)
[3] G. Suárez (personal communication, 1992).
[4] Astiz (1980).
[5] Composite fault plane solution, Havskov (1982).
[6] Rodríguez *et al.* (1984).
[7] Composite fault plane solution, E. Nava (personal communication, 1995).
[8] Composite fault plane solution, Campos *et al.* (1995).
[9] This study.
* Swarm.

The broadband station CUIG consists of STS-1 seismometers, FBA-23 accelerometers, and a 24-bit Quanterra digitizer with a GPS clock. PPM is a portable broadband seismograph with RefTek 24-bit digitizer and a Guralp CMG-40T seismometer, continuosly recording at 100 sps. A detailed description of the telemetered short-period network will be presented elsewhere.

(a) Location of the event

Generally, local events within the TMVB have very emergent first arrivals due to shallow focus and complex surface geological structure (Figure 3). For the event under study, the P arrivals were surprisingly impulsive at most stations (Figure 3). In some cases, however, it was difficult to read S waves because of saturation of the seismograms and also because of the arrival of a converted S to P phase, which sometimes masked the S waves.

Table 2

Crustal structure

Thickness (km)	P wave (α) (km/sec)	S wave (β) (km/sec)	Density (ρ) (x10³ kg/m³)	Q_α	Q_β
2.0	2.90	1.60	2.28	200	100
2.3	4.90	2.85	2.68	200	100
4.7	5.82	3.38	2.86	400	200
36.0	6.55	3.81	3.03	400	200
half space	8.10	4.70	3.32	800	400

The crustal structure used in the location is given in Table 2. The upper 5 km of this crustal structure is based on a refraction study in the Valley of Mexico (Havskov and Singh, 1977-78), on a few bore hole measurements (Marsal and Graue, 1969; Pemex, 1986), and seismic reflection profiling (Flores López, 1987; Pérez Cruz, 1988). Below 5 km the structure is based on a surface wave dispersion study by Campillo *et al.* (1995). The results from HYPO71 (Lee and Lahr, 1972) give an epicentral location of the earthquake (Figure 2) of 19.18° N, 98.97° W, near the town of Milpa Alta, with a depth of 12.5 km. Tests with other initial depths and reasonable crustal structures did not change the epicentral location by more than 1 km. The depth is more sensitive to the crustal structure and varied between 12 and 16 km.

(b) Waveform comparison

It is interesting to compare waveforms recorded at CUIG from the Milpa Alta event with those from an event which occurred at the edge of Lake Texcoco on April 30, 1994 (epicenter 19.44° N, 98.89° W; H≅1.5 km). The two events had similar amplitudes and epicentral distances (27 and 32 km, respectively). The depth of the Milpa Alta event (H=12.5 km) is much greater than the Texcoco event (H≤1.5 km) and the source-receiver paths are very different. It has been suggested that the April 30 event was not an earthquake but an explosion (J. Lermo, personal communication, 1995). As seen in Figure 3, the waveforms are radically different. The CU records for the Milpa Alta event appear normal whereas those for the Texcoco event show very long coda and harmonic beating. The latter seismograms are similar to those obtained in the Valley of Mexico from coastal earthquakes, but recorded on lakebed sites. The radiated energy from the shallow Texcoco event seems to have been trapped in the upper low-velocity layers of the valley. The records shown in Figure 3 may improve our current knowlegde of the cause of the dramatic amplification of seismic waves in the valley (see, e.g., Singh *et al.*, 1988; Ordaz and Singh, 1992; Singh and Ordaz, 1993; Singh *et al.*, 1995). Figure 3 provides an excellent example of the difficulty encountered in locating and determining focal mechanisms of shallow events in the TMVB.

(c) Focal mechanism

The polarity of the new stations was checked by comparision with the expected polarity of the first motions

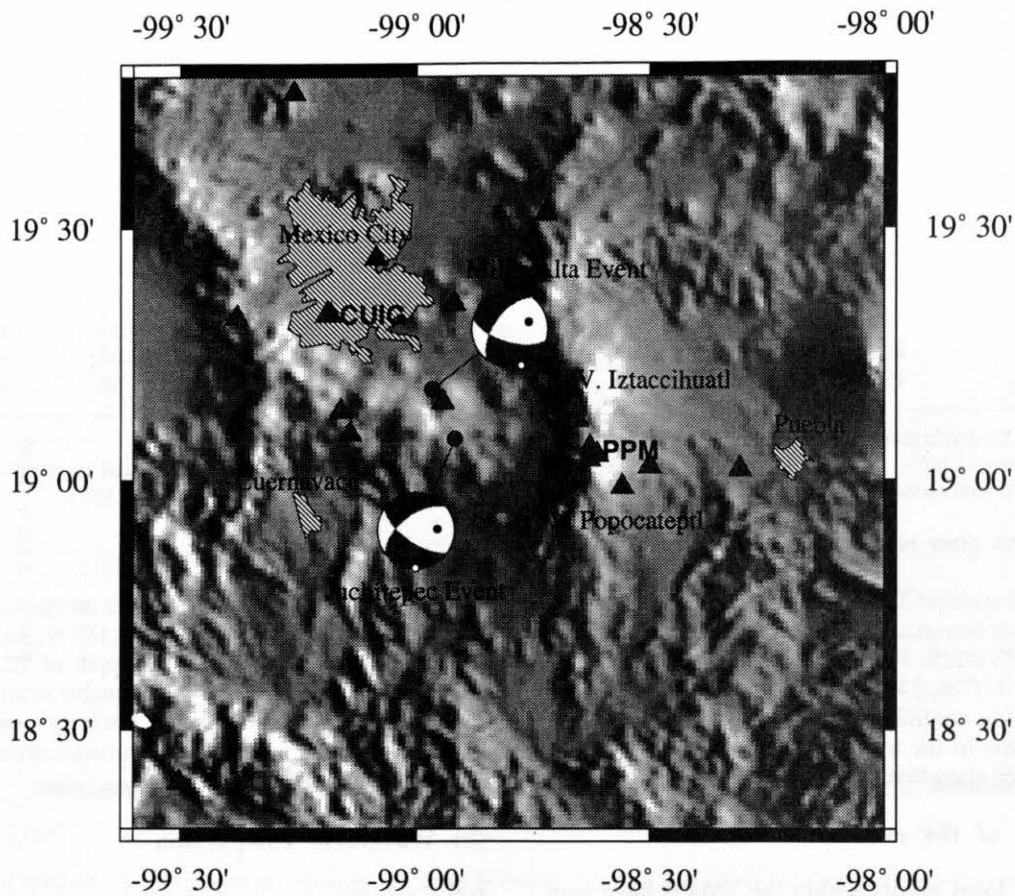

Fig. 2. Map of stations. Triangles show location of seismic stations used in this study. Stripped areas represent largest cities, and dark gray the volcanoes of Popocatépetl and Iztaccíhuatl.

from deep teleseismic and regional earthquakes. It was found that many stations had the wrong polarity. These polarities were corrected and plotted on an equal area projection of the lower hemisphere. As the first motions themselves could not constrain the two nodal planes, we developed an algorithm which utilizes the first motions as well as the waveforms of the broadband records. The procedure consists of:

1. Determining a range of strike, dip, and rake values which satisfies the first motion data.

2. Rotating and integrating three-component seismograms to obtain displacements and measuring amplitudes of P_z and SV_z on the vertical and SH on the transverse component. A file is then created with the polarities of the first P wave motion for single z-component seismographs, and the amplitude and polarity of P_z, SV_z and SH from three-component stations. This file also contains an a priori estimate of the error in the ratio of P_z/SH and SV_z/SH, and the number of inconsistencies in polarity that one wishes to allow.

3. A grid search is performed over the possible mechanisms obtained in step 1. For each mechanism, theoretical relative amplitudes of P_z/SH and SV_z/SH are computed. The ratios, as well as the polarities of P_z, SV_z and SH, are compared with the observed ones. This grid search reduces the number of acceptable focal mechanisms. Note that the comparison of the ratio takes into account the error specified in the file.

4. The remaining of mechanisms are tested by comparing the observed waveforms with computed synthetic seismograms.

Recall that the theoretical amplitudes and polarities are computed for a point dislocation in an infinite space. This procedure will be most adequate at stations within the S-wave window, especially for the SV_z component, since at greater distances, the SP phase invalidates the assumption of infinite space for the SV_z phase. For larger distances, P and SH relative amplitudes and polarities may still be used, provided that they are direct arrivals. Note also that we refrain from searching for a focal mechanism which satisfies the relative amplitudes of a given phase at two stations at the same time. This is because the site effects may be very different for any pair of two stations, so that the comparison might reflect the effect of the local geology rather than of the focal mechanism.

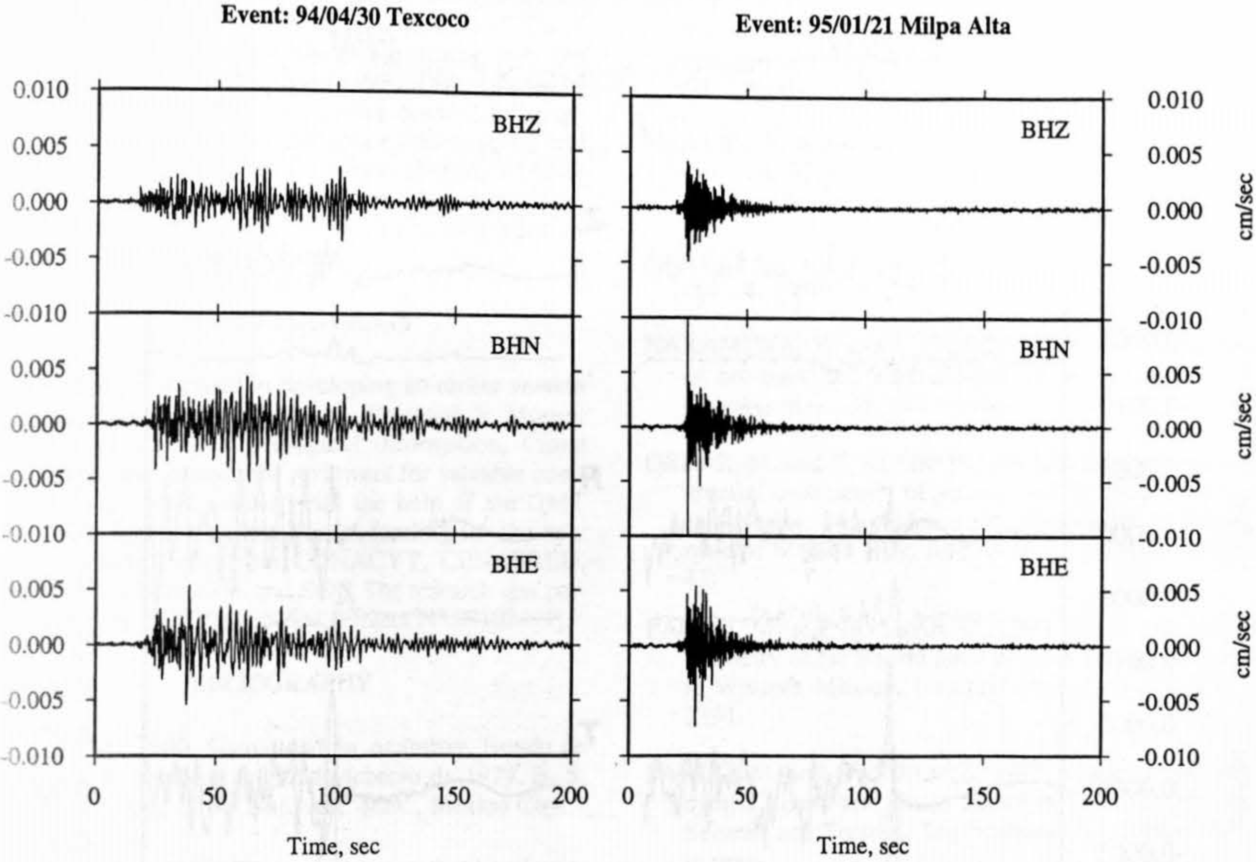

Fig. 3. Broad-band records from the Texcoco and Milpa Alta events registered at station CUIG.

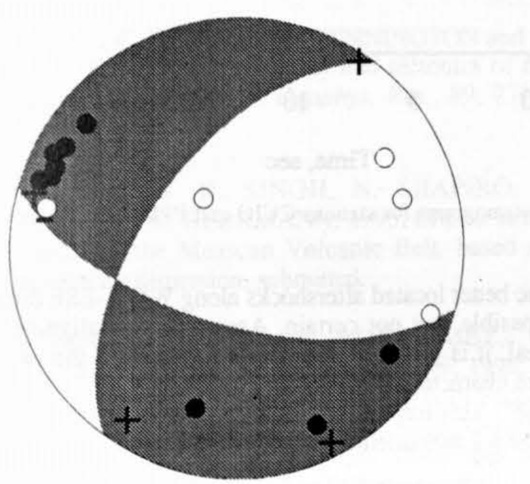

Fig. 4. Lower-hemisphere equal-area projection of the best fitting focal mechanism and first-motion P-wave polarities. Black circles and + symbols represent compressions and open circles and - symbol represent dilatations. The + and - symbols are for poor quality or nodal readings.

For the event under study, we supplemented the first motions from short-period vertical stations with the polarities and amplitudes of P_z and SH from the two broadband seismograms. Because of the large epicentral distance, we ignored the SV_z phase. We allowed for an error of 0.4 in the ratios, and we permitted no inconsistencies in polarities. Figure 4 shows the lower hemisphere equal-area projection of the focal sphere and the two nodal planes that satisfy the above constraints.

Figure 5 compares observed (top) and synthetic (bottom) seismograms at CUIG and PPM. Synthetics were generated using a discrete wavenumber summation algorithm (Bouchon, 1982) with the crustal model given in Table 2, an isosceles triangular source-time function with a base of 0.3 sec, and a seismic moment of 0.8×10^{21} dyne-cm ($M_w \cong 3.3$). In the computation of the synthetics we used constant values of $Q_\beta = 100$ and $Q_\alpha = 200$ for the first two layers and larger values for the layers below (Table 2). While this distribution of Q is only a guess, it is of no consequence in this study as we are interested only in the focal depth and the mechanism. In Figure 5 we show some synthetics corresponding to a focal depth of 12 km. Note that the synthetic S to P converted phase has a larger amplitude than in the observed seismogram, perhaps due to our poor knowledge of the crustal structure. The P and SH phases on the observed seismograms are, however, fitted adequately, giving us confidence in the focal mechanism and the depth of the event. Because of lack of knowledge of the crustal structure and the high frequency of the signals under study, we do not attempt a quantitative estimate of the misfit.

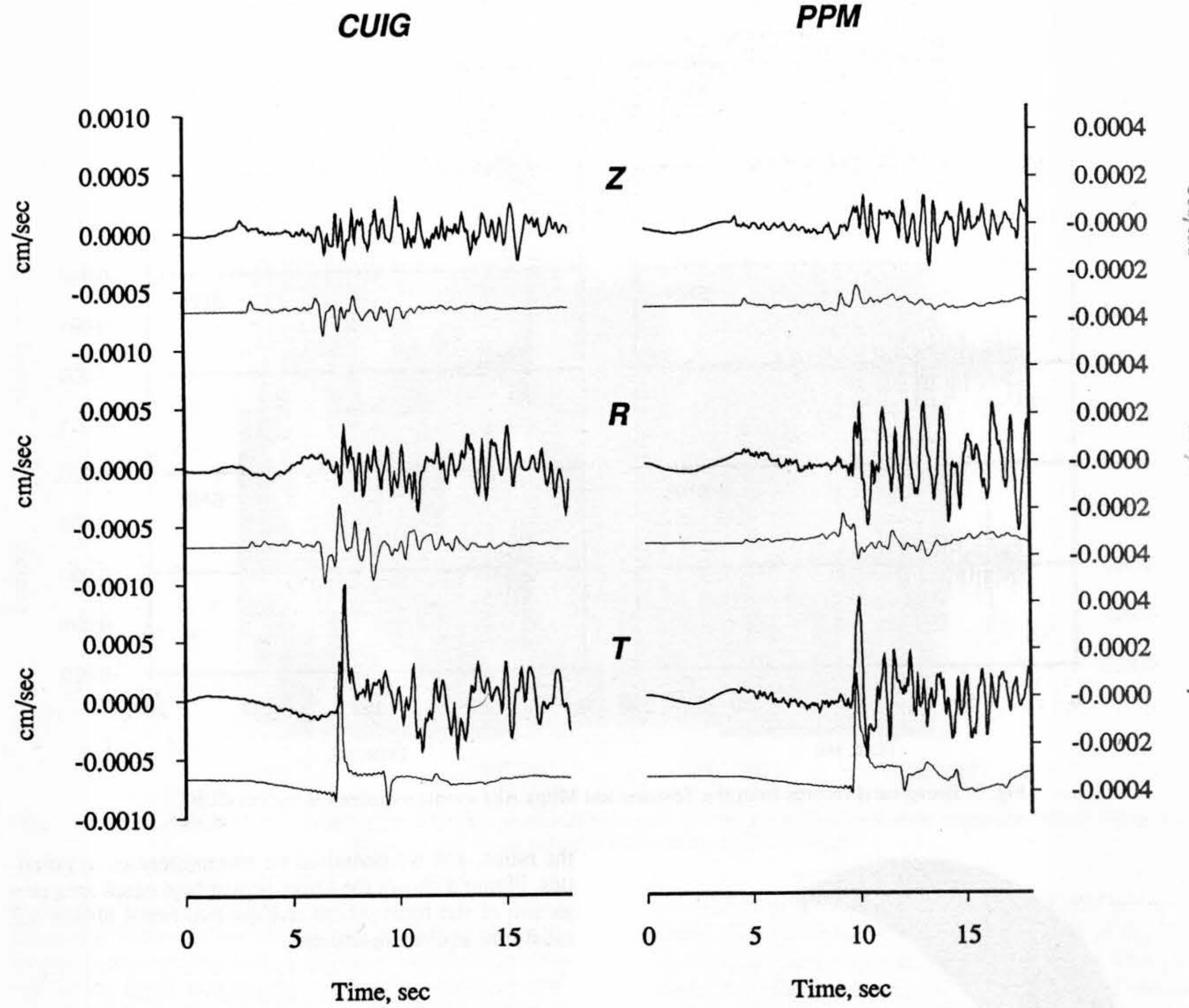

Fig. 5. Observed (top and darker) and synthetic (lower and lighter) seismograms for stations CUIG and PPM for the Milpa Alta event.

(d) Juchitepec event of February 7, 1984 (M_c=3.9)

This earthquake occurred close to the town of Juchitepec, near the epicenter of the Milpa Alta event. The location of the event was poor because of the reasons mentioned above. The aftershocks, however, were well recorded by portable seismographs which were deployed in the epicentral region soon after the mainshock (Rodríguez *et al.*, 1984). These events clustered around 19.12° N, 98.92° W. The focal depths of the well-located aftershocks ranged between 3 and 7 km, with an average depth of 5 km. The composite focal mechanism from these aftershocks (E. Nava *et al.*, in preparation) is shown in Figure 2 (see also Table 1). This mechanism is almost identical to that of the Milpa Alta event. Both earthquakes have normal-faulting mechanism with a significant strike-slip component (about 50%). There was considerable dispersion in the locations of the aftershocks (Rodríguez *et al.*, 1984). An alignment of the better located aftershocks along WNW-ESE direction is possible, but not certain. Assuming this alignment to be real, it is possible that the fault planes of the two events are characterized by a strike of 110°, dip 62°, and rake of -38°. This implies a normal fault with left-lateral motion, and a T axis oriented in a NS direction.

DISCUSSION AND CONCLUSIONS

The Milpa Alta earthquake of January 21, 1995 (M_c=3.9) is the best recorded earthquake to occur in the TMVB. The event was located at a depth of about 12 km. The focal mechanism of the event is very similar to the adjacent earthquake of Juchitepec, which occurred on February 7, 1984, although the depth of the Milpa Alta event is somewhat greater.

The two events have a normal-faulting mechanism with significant (about 50%) strike-slip component. If the nodal plane striking 110° is taken as the fault plane then these events involve left-lateral strike-slip motion. The T axis is essentially oriented NS, in agreement with the stress orientation mapped by Suter (1991, Figure 5), based on the alignment of Quaternary cinder cones. The agreement of stress orientation from geological mapping and from seismological analysis of a couple of small events is encouraging and suggests that the entire seismogenic zone, from the surface to a depth of about 12 km, in this part of the TMVB, is under NS extension.

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