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The Sanfandila earthquake sequence of 1998, Queretaro, Mexico: activation of an undocumented fault in the northern edge of central Trans-Mexican Volcanic Belt

F.R. Zúñiga[a,*], J.F. Pacheco[b], M. Guzmán-Speziale[a], G.J. Aguirre-Díaz[a],
V.H. Espíndola[b], E. Nava[a]

[a] Centro de Geociencias, UNAM, Campus Juriquilla, Apdo. Postal 1-742, Querétaro, Querétaro 76001, Mexico
[b] Instituto de Geofísica, UNAM, Cd. Universitaria, Coyoacán 04510, D.F., Mexico

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Abstract

A sequence of small earthquakes occurred in Central Mexico, at the northern edge of the Trans-Mexican Volcanic Belt (TMVB) in the State of Queretaro, during the first 3 months of 1998. Medium to large events in the continental regime of central Mexico are not common, but the seismic history of the region demonstrates that faults there are capable of generating destructive events. The sequence was analyzed using data from a temporary network with the goals of identifying the causative fault and its relation to regional tectonics. Employing a waveform inversion scheme adapted from a method used for regional studies, we found that the source mechanisms conform to the style of faulting (i.e. extension in the E–W direction) representative of the Taxco–San Miguel Allende Fault system. This system has been proposed as the southernmost extension of the Basin and Range (BR) Province. The spatial distribution of hypocenters and source mechanisms indicate that the seismogenic segment was a fault with an azimuth of approximately 334° with almost pure dip slip. Since events which occurred just south from this region show features which are consistent with TMVB tectonics (i.e. extension in an N–S direction), the sequence may mark the boundary between the TMVB and BR stress domains.

Keywords: Central Mexico; Basin and range; Crustal faulting; Trans-Mexican Volcanic Belt

1. Introduction

Current stress conditions of the continental crust in central Mexico have commonly been inferred from structural features such as fault trends, alignment of shield volcanoes, orientation of major dikes, well elongations, etc., (e.g. Suter et al., 1995) due to the scarcity of seismicity data. Recent studies have demonstrated that some of the faults which traverse central Mexico cut through rocks with documented ages younger than 750 ka (Suter et al., 2001). Only a handful of the known faults, however, have conclusively been shown to be active in late Quaternary times, even though some have been capable of generating destructive seismic events in historic times. Thus, the current seismic slip potential of the fault systems of central Mexico is still largely unknown.

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* Corresponding author. Fax: +52-442-238-1105.
E-mail address: ramon@geociencias.unam.mx (F.R. Zúñiga).

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The hypothesis that central Mexico is mainly influenced by the approximately N–S extensional tectonics of the Trans-Mexican Volcanic Belt (TMVB, Fig. 1) has been widely accepted (e.g. Suter et al., 2001). Other extensional systems with different orientations, however, appear to have an important role, if not the predominant one, in certain areas of central Mexico (e.g. Suter et al., 1995; Alaniz-Alvarez et al., 1998). These systems have not been studied in detail due to scarcity of seismic data and lack of detailed structural analyses. The TMVB is a mostly calc-alkaline volcanic arc which formed as a consequence of subduction of the Rivera and Cocos plates underneath the North American plate (Urrutia-Fucugauchi and Böhnel, 1987; Aguirre-Díaz et al., 1998). The TMVB strikes mostly east–west and comprises most of the main active volcanoes of Mexico (Fig. 1). It has been suggested (e.g. Pardo and Suárez, 1995) that the variable angle of subduction of the Cocos plate is responsible for the unique orientation of the TMVB, which does not run parallel to the trench.

Most of the deformation of the central part of the TMVB (Fig. 1) is being taken up by the Chapala–Tula fault zone (CTFZ, Johnson and Harrison, 1990), also known as the Chapala–Cuitzeo–Acambay system (Suter, 1991; Suter et al., 1995), which branches out east–west and comprises mostly normal faults. The arc-parallel fault zone, and the volcanic arc itself, are superposed on a nearly perpendicular preexisting stress and deformation province which may correspond to the extension of the Basin and Range (BR) into Mexico (Suter, 1991). This province has been called the "real southern Basin and Range" by Henry and Aranda-Gómez (1992), and comprises north–northwest to north–northeast-striking normal faults, some of which are grouped in the Taxco–San Miguel Allende Fault Zone (TSMFZ, Demant, 1978; Pasquaré et al., 1987; Nixon et al., 1987). According to Henry and Aranda-Gómez (1992), extension started as early as 30 Ma in areas north of the TMVB.

South of the city of Queretaro the two fault systems intersect (Figs. 1 and 2). Their interaction produced major blocks and a complex mosaic of smaller isolated blocks. Some of these blocks have fault orientations that depart from the trends of the two main systems, which are orthogonal with one another. Numerous Plio-Quaternary volcanic centers lie at the intersection of these two systems (Aguirre-Díaz and McDowell,

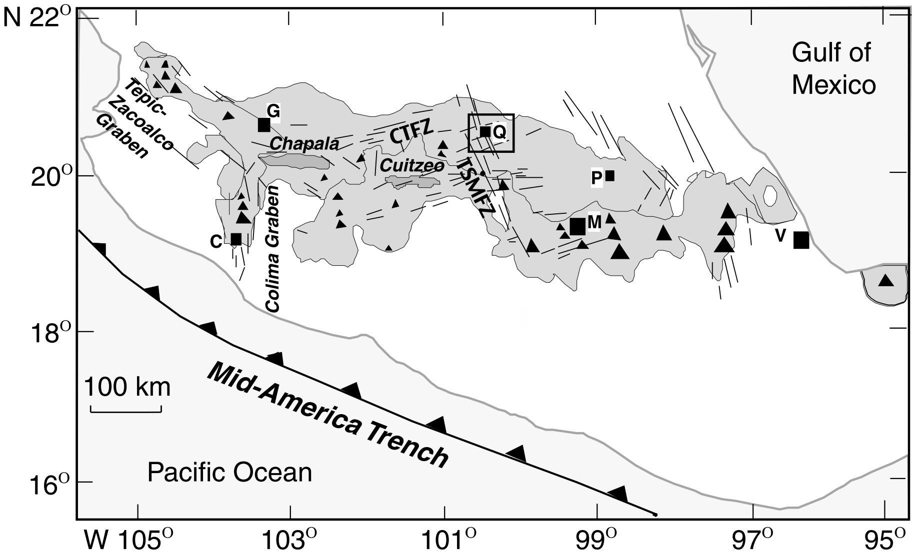

Fig. 1. Map of main structural tectonics in the TMVB. G = Guadalajara, C = Colima, Q = Queretaro, P = Puebla, M = Mexico City, V = Veracruz. Dark triangles are Quaternary volcanic edifices. CTFZ = Chapala–Tula Fault Zone, TSMFZ = Taxco–San Miguel Allende Fault Zone. The square indicates the area shown in Fig. 2.

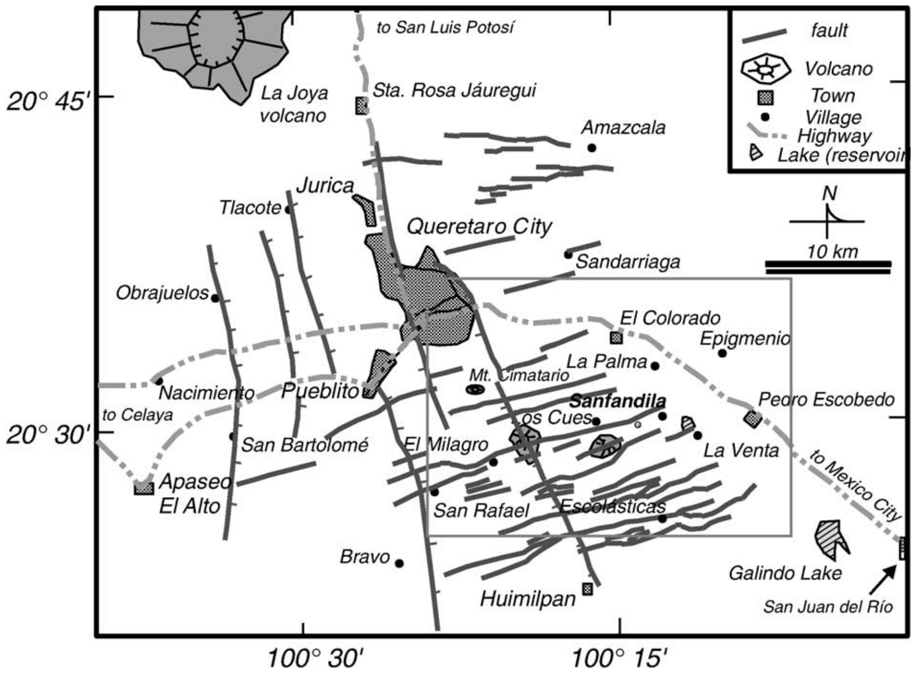

Fig. 2. Main faults and structural trends in the studied area. The gray square outlines the area shown in Fig. 4.

2000). Based on satellite and aerial imagery, Aguirre-Díaz et al. (submitted for publication) identified various major faults in the region (Fig. 2), aligned following both the WSW–ENE and NNW–SSE systems. No faults could be identified further to the east due to the alluvial sediment cover of the valley.

A sequence of small seismic events took place the first months of 1998, frightening the inhabitants of the small community of Sanfandila (hereafter, we will refer to the sequence as the *Sanfandila* sequence), located about 25 km southeast of the city of Queretaro near the Sierra Los Cués range. Events were felt almost every day for over 2 months, although none was strong enough to cause any damage to the masonry or adobe of the small buildings. Soon after the start of the sequence, a network of portable seismographs was installed to identify the origin of the activity and to investigate its characteristics. At the same time, faults in the region were evaluated in the field and from available satellite and aerial photographs. The main stratigraphic, geochronological and structural features of faults in the area are discussed in Aguirre-Díaz et al. (submitted for publication). In this study, we analyze the source characteristics of the earthquake sequence and discuss its implications for defining the tectonic boundaries of the TMVB and BR regions as well as for the seismic risk assessment in central Mexico.

2. Seismic activity and stress regime in central Mexico

Few seismic events related to the faults mentioned above are reported, but earthquakes in the continental crust have been known to cause serious damage in the past to populated areas in central Mexico (Fig. 3). The frequency of occurrence of damaging shallow crustal events in central Mexico is much lower than that of the large subduction zone events which affect the Pacific coast so precautionary measures in the building codes of the area are usually not considered. However, the risk of moderate events affecting populated areas is not negligible due to their shallow depth and proximity to large urban centers. The largest crustal event known to have occurred in central Mexico is the Jalisco event of

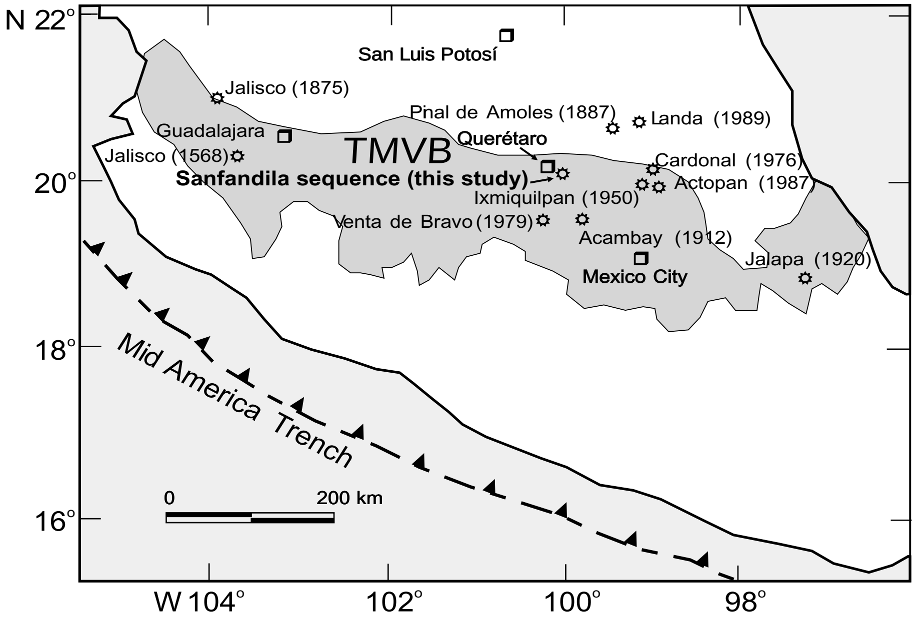

Fig. 3. Main crustal events (dented circles) in Central Mexico. The Trans-Mexican Volcanic Belt region is shown in dark gray.

December 27, 1568. Suárez et al. (1994) considered its magnitude in the $7.5 \leq M_w \leq 7.8$ range, based on a comparison with felt areas of more recent events. They regard this event as consequence of the Trans-Mexican Volcanic Belt (TMVB) stress domain. The crustal event, which caused the largest damage during the 19th century, is the shock of December 27, 1875, which took place near the city of Guadalajara. Suarez (personal communication) has calculated a magnitude of $M_w = 7.1$ for this event, based on magnitude-intensity regression. The largest crustal events, which occurred within central Mexico during the 20th century, are the November 12, 1912 Acambay earthquake with an estimated magnitude of $M_w = 7.0$ (Singh and Suárezy, 1987), and the $M_S = 6.4$ Jalapa event of January 3, 1920 (Suárez, 1992). The Jalapa event, even though it is seldom mentioned, caused approximately 650 deaths (Suárez, 1992), second only to the great 1985 Michoacan earthquake in terms of 20th century fatalities. Thus, it is of extreme importance to gather as much information as possible about the current state of stress in central Mexico, as well as about the seismic potential of faults located there.

Only three events with moderate magnitudes are known to have occurred north of the TMVB in central Mexico, neighboring the region where the Sanfandila sequence took place. The first is the Jalpan event that occurred on May 8, 1887, which caused panic among the local population. It fractured a church dome and damaged several houses (García Acosta and Suárez, 1996). It is unclear whether this event is related to the May 3, 1887, earthquake located in the Basin and Range (Suter and Contreras, 2002; Natali and Sbar, 1987), which shocked northwestern Mexico and southwestern US.

A few months later, the Pinal de Amoles earthquake (Fig. 3) took place on November 26, 1887, damaging various nearby towns (García Acosta and Suárez, 1996). The latter event is well documented (Orozco y Berra, 1887) and its magnitude has been estimated as $M_i = 5.3 \pm 0.5$ (Suter et al., 1996), based on isoseismal areas and maximum intensity. More recently, an event near the town of Landa occurred on September 10, 1989 to which the Servicio Sismológico Nacional assigned a magnitude of $M_c = 4.6$. No late Quaternary faults have been identified as the source of any of these events because no faults in the epicentral or mesoseismic regions are apparent from geological observations. Thus, it is uncertain whether these events are related to the same fault system. However, Suter et al. (1996), on the basis of isoseismal geometry as well as the existence of a north–south lineament near the epicentral area of the Pinal de Amoles earthquake, have hypothesized that this event may be related to the southern extension of the BR.

Different styles of faulting are observed in the TMVB region. These may be due to the balancing of stresses induced by gravity on the high topography of the belt, and those transmitted by the plate interaction at the Middle America thrust (Dewey and Suárez,

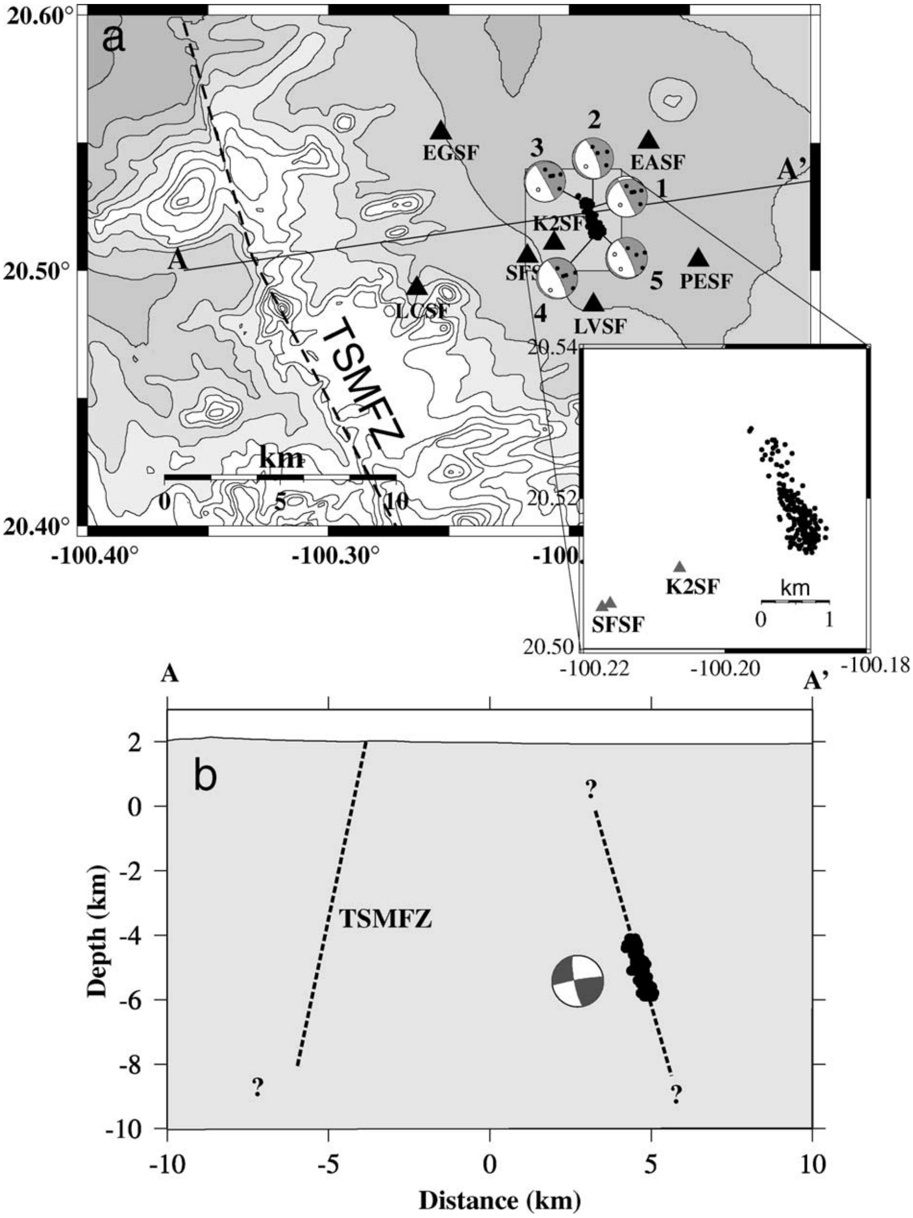

Fig. 4. (a) Epicenters of the Sanfandila sequence and fault plane solutions for the largest events found by the inversion procedure described in the text. Dashed lines are the main inferred faults in the area, based on satellite imagery and field recognition. Profile line A–A′ used for cross-section is indicated. (b) Cross-section A–A′ with hypocenters.

1991), or to different stress regimes controlling each region (Suter et al., 2001). Nevertheless, the most common mechanism observed at the TMVB is extension oriented in a nearly north–south direction, that is, perpendicular to the present trend of the TMVB. The depth of events located within the TMVB region is generally shallower than 20 km. As mentioned above, the Acambay, 1912 and the Jalapa, 1920 earthquakes are the largest events registered during the 20th century in the TMVB region. However, they took place further south into the volcanic arc and apparently agree with north–south extension, thus belonging to state of stress expected for the TMVB.

Suter et al. (1996) analyzed the isoseismal characteristics of three other events in central Mexico: Ixmiquilpan, 1950 ($m_b = 4.9$), Cardonal, 1976 ($m_b = 5.3$), and Actopan, 1987 ($m_b = 4.1$), all of which occurred in the northern section of central TMVB (Fig. 3), about 100 km southeast of the events mentioned before. Nearby late Cenozoic normal faults (such as those belonging to the Aljibes and Mezquital grabens) trend approximately E–W; isoseismals for the largest intensities of these events tend to elongate in a N–S direction, except in the case of the Actopan event of 1987 which does not clearly define a major axis. To present date, the Sanfandila sequence is the only sequence in Central Mexico north of the TMVB ever studied in detail.

3. Data analysis

A temporary monitoring network, consisting of four broadband portable stations, two digital accelerographs and two smoked paper seismographs, was installed near the town of Sanfandila about 25 km southeast from the city of Queretaro (Fig. 2). The broadband stations consisted of RefTek 24 bit digitizers connected to Guralp CMG-40T broadband sensors. The accelerographs were Etna 18 bit digitizers from Kinemetrics connected to FBA-23 sensors. The network started operation on January 8, and remained in place for 2 months. The location of stations is shown in Fig. 4. We registered over 200 events of which a total of 179 events were suitable for hypocentral location (Fig. 4a) and magnitude estimation (see "Electronic Supplements" on the journal's homepage http://www.elsevier.com/locate/tecto). To locate the events, we used the program *Hypocenter* [URL for program: elepaio.soest.hawaii.edu anonymous login, ftp/pub/lienert](Lienert and Havskov, 1995) and the crustal velocity model shown in Table 1, which is a modified version of the structure determined by Fuentes (1997) from surface wave dispersion of Rayleigh waves across the TMVB. The horizontal error in the locations is less than 0.8 km and the vertical error less than 1 km on average. The largest events of the recorded sequence had $M_w \approx 3.5$ (coda magnitude $M_c = 2.4$) although it is possible that a larger event in the episode was missed because it occurred before the network was installed. Epicenters align following an azimuth of approximately 343°, parallel to the main trend of the Taxco–San Miguel de Allende fault. The topographic expression of this large fault can be observed in Fig. 4, just west of the located events. A cross-section is shown in Fig. 4b indicating that hypocenters cluster following an steeply dipping plane.

We selected the events with the largest signal to noise ratio for waveform modeling and determined focal mechanism and scalar seismic moment. The largest earthquake analyzed had $M_w = 3.0$ and occurred on January 25 at 09:57. The largest events in the recorded sequence were doublets, so we were unable to use them for inversion purposes because the method employed cannot differentiate complex sources. The method used is similar to that described in Pacheco et al. (1999) and is adapted from the regional inversion scheme of Randall et al. (1995). P, SV and SH waves from all the broadband stations are integrated to obtain displacement, and then band-pass filtered between 5 Hz and 5 s The observed seismograms are inverted, in a least square sense, for focal parameters and scalar seismic moment. The earthquake depth was fixed to that obtained from the location. Because these events are small, the source is practically a point source and the hypocenter can be

Table 1
Velocity structure used in the location procedure

Depth (km)	V_p (km/s)	V_s (km/s)
0.0	4.15	2.40
2.2	5.06	2.92
5.2	6.10	3.52
7.0	6.29	3.63
20.3	7.45	4.30
99.0	8.04	4.64

considered the centroid depth. Focal parameters may then be retrieved from the low frequency signal of the seismograms (0.2–5 Hz), eliminating the noise produced by high frequency scatter waves and unknown crustal structure details. Fig. 5 shows observed P, SV and SH waves and best fitting synthetic seismograms obtained after the inversion, for the event of February 5, at 22:33 (M_w 2.5). First motion polarities are also shown in the figure to compare with the solution obtained through waveform inversion. We determined focal parameters of five events (Fig. 4, Table 2) for which the mean azimuth of the fault planes is 334 ± 3° and the mean dip is 82 ± 6°. In order to show that low frequency analysis of the P, SV and SH seismograms is enough to retrieve the source parameters, Fig. 6 compares complete synthetic seismograms determined through the wave number integration algorithm of Bouchon (1982) with the observed waveforms for a representative event in Table 2. Not only the amplitude and phase of the main phases are matched by the synthetic but also near and intermediate wave-fields. Higher frequency complexities, which are not modeled, are due to unknown crustal structure and shallow sedimentary layers in the basin. Other events analyzed showed basically the same features. Further comparisons showed that the same basic features of the larger signals analyzed pervaded in most of the small signals, so we interpret this as an indication that most of the events were originated by similar if not the same type of faulting mechanism (normal quasi dip slip). Thus, both the focal solutions and the spatial hypocenter distribution indicate that the fault activated during the earthquake sequence in

Table 2
Earthquake source parameters of best fit solutions from the Sanfandila sequence

Date	h:min	Lat	Lon	h	M_w	φ	δ	λ
19980123	04:56	20.525	− 100.190	4.8	2.9	333	89	− 108
19980123	05:16	20.526	− 100.190	4.8	2.2	338	76	− 91
19980123	06:53	20.526	− 100.192	4.8	2.0	331	87	− 98
19980125	09:57	20.515	− 100.188	5.2	3.0	332	79	− 89
19980205	22:33	20.515	− 100.187	5.6	2.5	334	80	− 87

M_w = moment magnitude, φ = strike, δ = dip, λ = rake, h = depth (km).

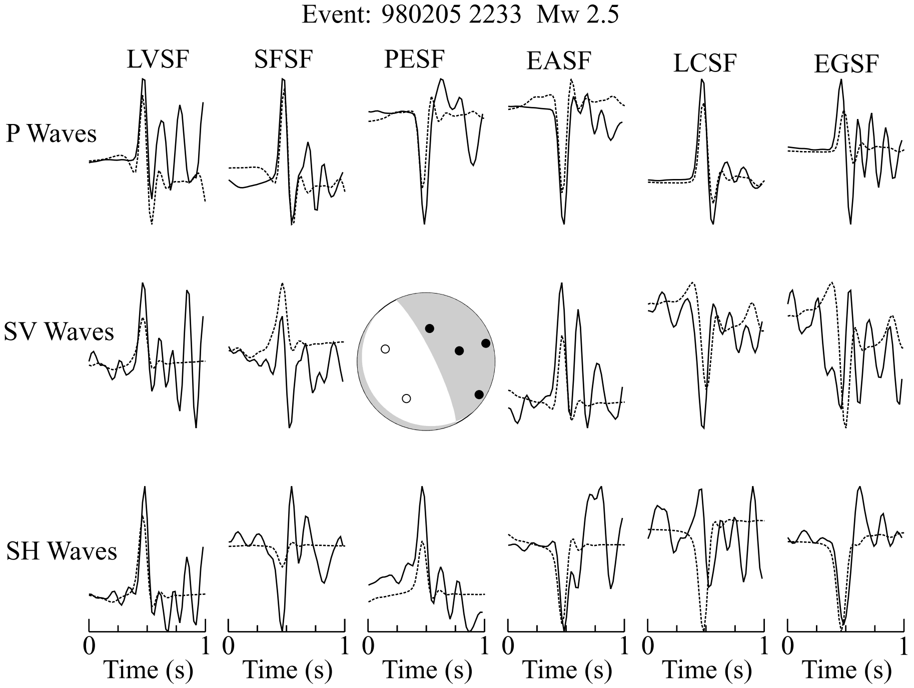

Fig. 5. Normalized observed (solid) and synthetic (dashed) waveforms for one of the representative events (February 5 at 22:33). Focal mechanism that best fits observed seismograms. First motion polarities are shown to compare with best solution.

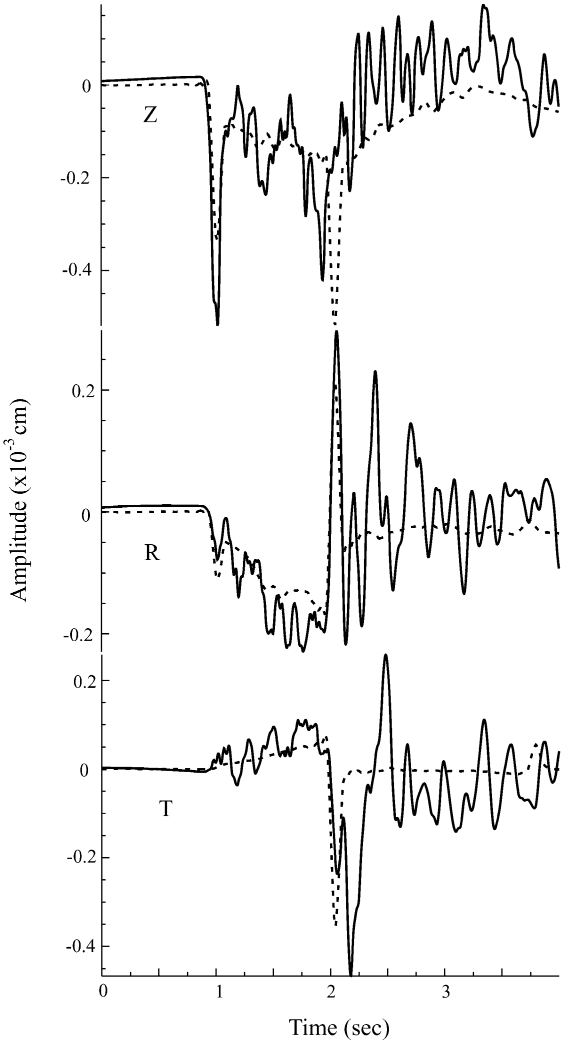

Fig. 6. Synthetic seismograms of complete waveform determined by wave number integration for the event which occurred on January 25 (see Table 2), as compared to the observed signal recorded by station LVSF.

Sanfandila, is a normal fault with an azimuth of ∼ 334° which dips to the east at a steep angle (80°).

4. Discussion

Nieto-Samaniego et al. (1998) argued that deformation in central Mexico (at the southern Mesa Central) is three-dimensional with extension in the horizontal plane. They calculate an amount of extension of 20% oriented approximately E–W, and conclude that the peak of extension post-dates the principal volcanic episodes. Suter et al. (1995), on the other hand, conclude that BR features seen in the Aljibes half-graben area appear to have been active at approximately the same time than the east-striking normal faults of the graben. Aguirre-Díaz et al. (submitted for publication) have shown that the N–S faults in the Sanfandila vicinity may have been reactivated in recent times because they appear to have displaced E–W faults from a relatively younger system, the Chapala–Tula fault zone.

The Sanfandila sequence thus evidences that a small segment of a fault with the same N–S tendency as other faults in the region reactivated, indicating that the system itself is active. This system follows the trend and faulting style of the proposed southern extension of the BR province (Henry and Aranda-Gómez, 1992). On the other hand, medium-sized crustal events, which occurred south from this region (e.g. Acambay, 1912, Venta de Bravo, 1979, Fig. 3) as well as the small events which occurred to the south–east (Campos-Enríquez et al., 2000; UNAM and CENAPRED Seismology Group, 1995; Suárez and Ponce, 1986) all indicate normal faulting striking in the E–W direction. Furthermore, a sequence of events similar to that of Sanfandila which took place during May–June 2000 east of the Aljibes Graben, southeast from the events analyzed here, also show fault plane characteristics following the E–W trending of the TMVB system (Servicio Sismológico Nacional, 2000). Thus, the Sanfandila sequence may mark the boundary between the TMVB and BR provinces in Central Mexico, where the minimum compressive stress direction abruptly changes from E–W to N–S. Aranda-Gómez et al. (2000) and Alaniz-Alvarez et al. (1998) agree that in Central Mexico, volcanism and faulting, may have been simultaneous at different stages. As already mentioned, the region east from the Sanfandila sequence also exhibits similar characteristics of recent N–S active faulting even though the main structures there (Mezquital Graben, Aljibes half-Graben) follow an E–W tendency. Suter et al. (1995) measured a very low stress ratio $\bar{\sigma} = \sigma_2 - \sigma_3/\sigma_1 - \sigma_3$ in the Aljibes half-graben. This low ratio means that σ_2 and σ_3 (the intermediate and least principal stresses) have very similar magnitude and hence are interchangeable. If this is so, small perturbations in the local stress field will produce N–S or E–W principal stresses.

5. Conclusions

A small earthquake sequence that took place during the first days of 1998 near Sanfandila, in the Mexican State of Queretaro, was investigated in order to infer its implications for the activity of fault systems in Central Mexico. Two main structural features characterize the region where the sequence took place. The E–W trending Chapala–Tula Fault Zone and the N–S Taxco–San Miguel de Allende fault system. South of the city of Queretaro, these two important fault systems intersect. Very little is currently known about the actual state of stresses in central Mexico, so gathering as much information as possible about stress release is of utmost importance, due to past occurrence of damaging events.

The location and depth of the sequence, as well as the source parameters of the largest events derived from waveform inversion, suggest that a fault with an average azimuth of 334° and almost pure dip slip was the causative fault. Such style of faulting is consistent with the overall pattern of faults belonging to the TSMFZ, which in turn may be considered the southern extension of the BR stress province. Furthermore, the location of the events and the style of faulting may mark the boundary between the BR and the TMVB provinces since events which had been previously studied south–east from this region show features which are consistent with TMVB tectonics and belonging to the CTFZ. This sequence is evidence that faults belonging to the TSMFZ are active and that an E–W minimum horizontal compressive stress is the dominating tendency north of the TMVB. We cannot rule out the possibility that both systems (CTFZ and TSMFZ) reactivate in the future since episodes of alternating activity seem to be part of the history of deformation in Central Mexico.

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