Seismicity, focal mechanisms, and stress distribution in the Tres Vírgenes volcanic and geothermal region, Baja California Sur, Mexico

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RESUMEN

En octubre de 1993 se llevó a cabo un monitoreo sísmico en la región volcánica Las Tres Vírgenes con el propósito de registrar la actividad sísmica asociada a las estructuras volcánicas, al campo geotérmico y a la tectónica local. Se localizaron 257 microsismos con hipocentros en los edificios volcánicos y a lo largo de la falla de rumbo, lateral derecha conocida como falla La Virgen. La profundidad focal de los sismos varía desde los muy cercanos a la superficie de la Tierra hasta los 8 km. Las profundidades someras ocurren principalmente en los edificios volcánicos. Los sismos más profundos ocurren fuera del área volcánica. La magnitud de duración de los microsismos localizados varía entre 1 y 3. La razón Vp/Vs y los valores bajos de Q que se estimaron en la zona sugieren un material con propiedades heterogéneas bajo las estructuras volcánicas, principalmente hacia la falla el Azufre y la caldera El Aguajito, donde se ha reportado la actividad hidrotermal. La distribución de los ejes P y T de los mecanismos focales de 90 microtemblores sugieren que la región se encuentra bajo compresión en dirección N-S y extensión en dirección E-O, en concordancia con el régimen de esfuerzo regional impuesto por el sistema de fallas transformadas, NO-SE, lateral derecho, del Golfo de California.

PALABRAS CLAVE: Sismicidad, mecanismos focales, esfuerzos tectónicos, campo volcánico, geotermia, Baja California Sur.

ABSTRACT

In October 1993 we carried out a seismic monitoring in the Tres Vírgenes volcanic region in order to record the background seismicity associated with the volcanic structures, the geothermal field and the tectonic features of the area. Hypocenters for 257 microearthquakes were located in the volcanic edifices and along the northwest right-lateral, strike-slip La Virgen fault. Focal depths range from close to the Earth surface to about 8 km. Shallow depths occur mainly in the volcanic edifices. Deeper seismic events occurred outside the volcanic area. The duration magnitudes of the located microearthquakes range between 1 and 3. The Vp/Vs ratio and the low-Q values estimated suggest heterogeneous material properties in the volcanic structures mainly toward the El Azufre fault and the El Aguajito Caldera, where hydrothermal activity has been reported. The P- and T-axes of focal mechanisms for 90 microearthquakes suggest that the region is under N-S compression and E-W extension, in agreement with the regional tectonic stress field of the NW-SE right-lateral strike-slip transform fault system of the Gulf of California.

KEY WORDS: Seismicity, focal mechanisms, tectonic stress, volcanic structures, geothermal field, Baja Califonia Sur.

INTRODUCTION

Tres Vírgenes is the name of an area of three stratovolcanoes aligned in a NE-SW direction in the central part of Baja California peninsula (Figure 1). The volcanoes in this group are known as La Virgen, El Azufre, and El Viejo (Sawlan, 1981). The most recent volcanic activity in the area occurred in 1746 and was associated with La Virgen volcano, the youngest of the complex (Ives, 1962; Sawlan, 1981).

Hot springs and fumaroles have been observed at scattered locations throughout the Tres Vírgenes volcanic complex. The region was considered as a potential geothermal resource area. Since 1983, geological, geochemical and geophysical studies have been carried out in the region by the Comisión Federal de Electricidad (CFE), the Mexican federal power commission (Campos-Enríquez, 1992; Sánchez-Velasco, 1996; López, 1998). In 1986 an exploratory well was drilled in the thermally active zone. After this, CFE drilled up seven more wells in the zone, to depths between 1200 and 2150 m. Temperatures went from 110° to 260° C (Lira *et al.*, 1997). In this hydrothermally altered region the higher elevations contain fumaroles and steaming fields. At lower levels small hot springs can be found. The main results of the studies are summarized in

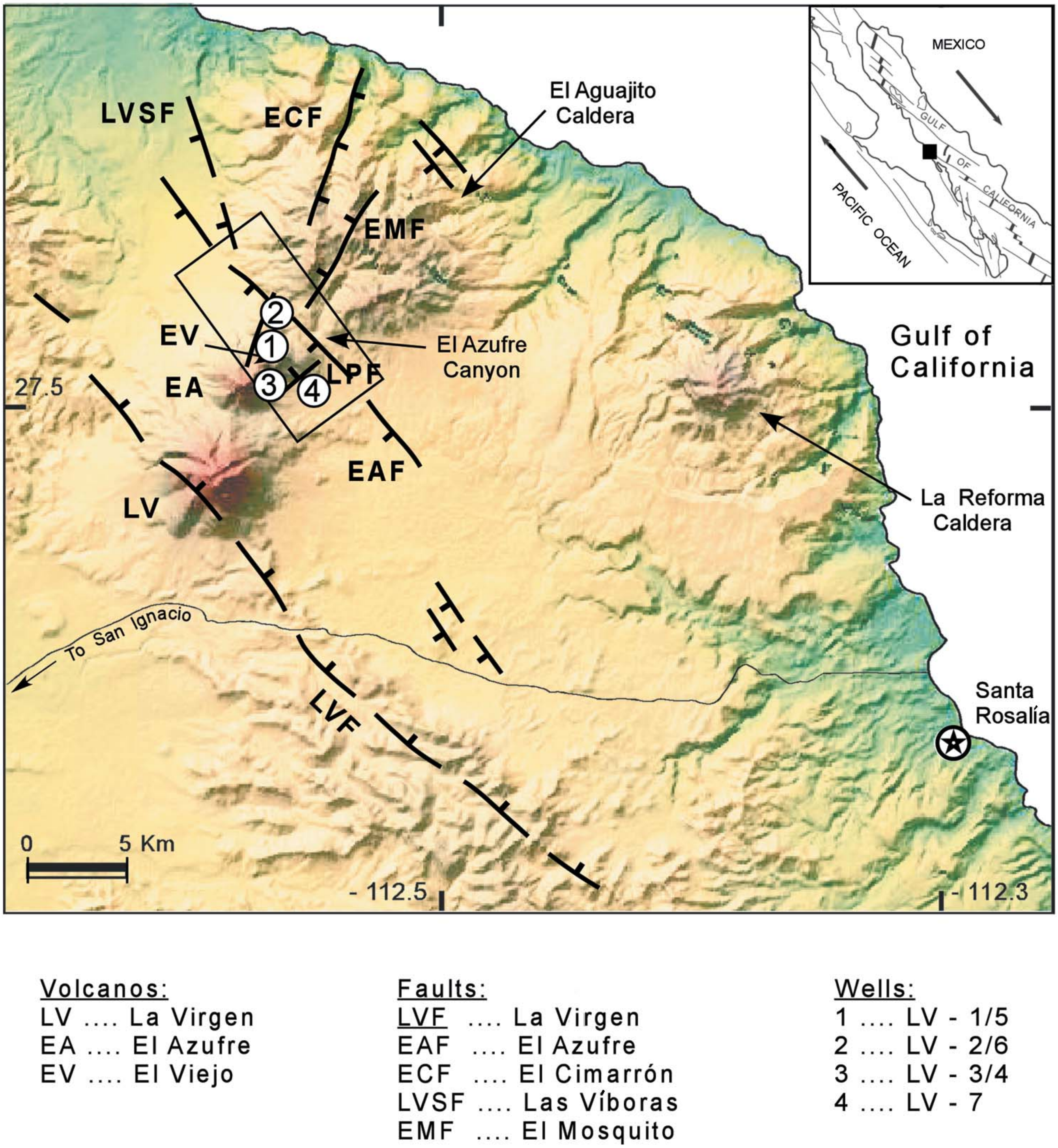

Fig. 1. Map of the Tres Vírgenes volcanic region showing the location of the major faults and volcanic structures. Also shown are the locations of the boreholes (LV) and the geothermal field in the area (rectangle). The inset displays the location of the Tres Vírgenes volcanic region on the Baja California peninsula.

López *et al*. (1995). The development of the geothermal field is still in progress.

Results from seismological studies as well as from different geophysical surveys including magnetotellurics (MT), transient electromagnetics (TDEM) and direct current-resistivity vertical soundings (Schlumberger) have been recently summarized by Romo *et al*. (2000). Those studies found that geothermal fluids may exist in some localized zones of the granodioritic basement, at depths of about

1200 m, pressures of ~120 bars, and temperatures near 240° C. At such depths the permeability has been increased due to an intense fracturing of the rocks (López *et al*., 1995). Such studies suggest that highly fractured rocks with fluids and high temperatures at depth may affect the attenuation of the seismic waves, as well as the electrical conductivity.

Digital and analog data from local microearthquakes recorded in October 1993 with a portable seismic network are used to study the seismic activity, the focal mechanisms and to investigate their tectonic significance. During its 23-day period of operation, the portable network recorded data for a large number of microseismic events. Hypocenters for 257 events could be obtained with data from at least five stations. The microearthquakes used in this study were classified as volcano-tectonic (VT) earthquakes, according to the classification method of Miller *et al*. (1998) or Lahr *et al*. (1994), among others. The seismograms produced by these events were characterized by high frequencies and clear P- and S-wave arrivals. Other type of volcanic earthquakes was also observed in our recording period. However, these other events were characterized by the absence of secondary phases and they were not located. A better knowledge of the seismicity pattern, the attenuation of the seismic waves, the Vp/Vs ratio, and the stress distribution in the study area will complement the results reported in previous geophysical studies.

GEOLOGIC AND STRUCTURAL SETTINGS

The first detailed studies of the volcanism and its relation to tectonic structural features in the Tres Vírgenes area were made by Colleta and Angelier (1981), Demant (1981), Ortlieb (1981), and Sawlan (1981). Those studies suggest that the Tres Vírgenes volcanic complex (El Viejo, El Azufre and La Virgen volcanoes) is the northwestern portion of the Santa Rosalía basin, which is controlled by the Gulf of California deformation system. The geological setting of the Tres Vírgenes region consists of Mesozoic granitic rocks overlain by late Cenozoic to Quaternary volcanic rocks (Gastil *et al*., 1975). This volcanism is considered as part of the magmatism related with the evolution of the Gulf of California (Gastil *et al*. 1975, 1979).

Figure 1 shows the most prominent geomorphic features recognized in the Tres Vírgenes volcanic area. These features are, from oldest to youngest, (1) the La Reforma Caldera (1.6-1.4 Ma), (2) the Aguajito Caldera (0.9-0.5 Ma), and (3) the Tres Vírgenes volcanic complex (0.44 Ma to present) (López *et al*. 1994). This figure also shows the El Azufre Canyon, which is the natural boundary between the Tres Vírgenes complex and the Aguajito Caldera. La Reforma and Aguajito Calderas have been considered as resurgent domes (Garduño-Monroy *et al*. 1993; Demant, 1981).

The oldest rock found in the region is a granitic rock of Cretaceous age (91.2 ± 2.0 Ma), which probably forms the regional plutonic basement in the Tres Vírgenes area (Schmidt, 1975). Overlaying this intrusive rock is a late Cenozoic volcanic cover that includes the Sierra Santa Lucía andesite, the northern limit of the Comondú Formation, and the Esperanza basalt (Sawlan, 1981). Beneath this volcanic cover is the Santa Rosalía Formation, which consists of shallow-water marine deposits characterized by fossiliferous sandstone. At the top of the above sequence there is a variety of pyroclastic products related to different stages of recent volcanism of the Tres Vírgenes complex (Sawlan, 1981). Chemically, the volcanic rocks emitted at the Tres Vírgenes volcanic region correspond to the calc-alcaline series, excepting an alcaline rich pyroclastic flow at La Reforma Caldera, which is marginally peralkaline (López *et al*., 1995).

The eruptive history of the Tres Vírgenes volcanic complex is predominantly characterized by effusive activity but an exceptionally Plinian eruption occurred about 6500 years ago at La Virgen volcano (Capra *et al*., 1998). The absence of younger volcanic deposits in the area suggests that the historic volcanic activity reported at La Virgen volcano in 1746 by a Spanish Jesuit was not probably associated to magmatic activity, although such historic observation was probably due to a landslide on the edifices of the volcanic complex, fumarolic activity, or small phreatic eruptions (Sawlan, 1981; Capra *et al*., 1998).

At the study region, the highest fault density is observed near the El Azufre Canyon and around the hydrothermal zone that is outlined by a rectangle in the Figure 1 (López *et al*., 1995). Preferential directions of faulting in the zone are NW-SE (La Virgen, Las Víboras, and El Azufre faults), N-S (Las Cuevas and El Cimarrón faults), and NE-SW (La Puerta and El Mosquito faults). López *et al*. (1995) suggested that the main fault system that controls the active hydrothermalism in the zone is the NW-SE Las Víboras-El Azufre system.

PREVIOUS SEISMOLOGICAL STUDIES

An exploratory experiment, consisting of a single seismic station operated in the Tres Vírgenes area from May to October of 1992, recorded more than 2000 events with S-P times of less than 3 sec and magnitudes between 1 and 3 (Wong and Munguía, 1992). After that initial seismic monitoring, CFE deployed six digital stations around the Tres Vírgenes volcanic complex. Results from analyses of data produced in the first four months of network operation show that the Tres Vírgenes seismicity does not occur at random. Rather, the seismic events occur spatially clustered along the volcanic structures and to the southeast of the volcanoes (Munguía and Wong, 1993, 1995). A large proportion of the recorded seismicity was located within the area covered by the seismic network. The duration magnitudes calculated for all the located events ranged from 1 to 3 and the focal depths between 1 and 12 km.

The estimated composite focal mechanism solutions indicate strike-slip and normal faulting. Most of the obtained focal solutions showed oblique faults, combining strike–slip and dip-slip motion. The variability of the focal mechanisms, as well as the occurrence of microearthquake swarm-like sequences reflects the structural complexity of the zone.

Results from recent seismic studies carried out in the Tres Vírgenes volcanic region suggest the presence of a low P-wave velocity and low-Q body around the El Azufre Canyon (Macías, 1997; Wong, 2000; Wong *et al*., 2001). Those studies found low coda Q values and low P-wave velocity anomalies along the El Azufre Canyon, where dense fracturing, hydrothermal activity (hot springs and fumaroles), and high temperatures have been reported (López *et al*., 1995). In this particular region, multiple geophysical surveys including magnetotellurics (MT), transient electromagnetics (TDEM) and direct current-resistivity vertical soundings (Schlumberger), permitted to outline the presence of a highly conductive zone along El Azufre Canyon, the limit between the Tres Vírgenes volcanic complex and the Aguajito Caldera (Romo *et al*., 2000).

DATA AND ANALYSIS

On October 1993, 13 portable analog and digital seismic stations were deployed in the Tres Vírgenes volcanic region for a 23-day period of recording (Figure 2). The purpose of this effort was to record the local seismicity and get precise hypocenter locations. The installed instrumentation consisted of six analog seismographs (Sprengnether, MEQ-800), coupled with 1-Hz vertical-component seismometers (Ranger-SS1, Kinemetrics), and seven three-component digital recorders (SSR-1, Kinemetrics), coupled with 1-Hz seismometers (Mark L-4C). The digital stations operated in an event-triggered mode and recorded at a nominal rate of 100 samples/sec on each channel. Timing for the analog seismic records was provided through internal WWVB radio time receivers. For the digital recorders, a common and absolute time base was achieved using the Omega radio time signal. Figure 3 shows examples of seismograms from a local earthquake recorded by the digital temporary seismic stations.

Stations deployment and event locations

All the recording stations were installed on volcanic rocks with an average distance among adjacent stations of less than 7 km (see Figure 2). During its 23-day period of operation, this portable network recorded more than 800 microearthquakes, including a microearthquake swarm-like sequence of at least 110 events and a three-day duration. This microearthquake swarm-like sequence was mainly observed at the analog seismograms. From the recorded seismic data, hypocenters for 257 seismic events could be estimated with the P- and S-wave phases from at least five stations. Seismic events that were too small to be located with five stations are not reported in this study. Most of the located events occurred within the area covered by the seismic network. A large proportion of these microseismic events were located in the volcanic edifices of the Tres Vírgenes volcanic complex, the Aguajito Caldera, and along the northwest right-lateral, stike-slip La Vírgen fault. Some of these microearthquakes occurred as clusters of events and as swarm-like sequences. These events occurred at focal depths between the Earth surface and 8 km, and had duration magnitudes between 1 and 3. Shallow depth events occurred mainly in the volcanic edifices.

The one-dimensional P-wave velocity model used in the hypocenter locations was taken from Munguía and Wong (1993, 1995). This velocity model was determined from the results of Thatcher and Brune (1973), Phillips (1964) and from log-density data of the LV-2 borehole (Viggiano, 1992). Figure 4 shows our 1-D P-wave velocity model and the velocity models determined by Thatcher and Brune (1973) and Phillips (1964). In order to estimate the S-wave velocities, we selected 60 microearthquakes with clear P- and S-phases to construct Wadati plots. Figure 5a shows the average Vp/Vs ratio of 1.72 ± 0.08 calculated for the whole region. This value was used in the hypocentral determination of all the located seismic events in this study.

The computer program HYPO71 (Lee and Lahr, 1975) was used to locate the seismic events. The accuracy of the arrival time picks generally depended on the nature of the phase onset and the background noise. Errors of the P- and S-waves arrival times picks are between ± 0.01 and ± 0.05 seconds in the digital records. On the analog seismograms errors in the P-wave time readings are of the order of 0.05 seconds. The rms residuals of epicenters are less than 0.3 seconds. Events within the network have vertical and horizontal location errors of less than ± 3 km. Events located outside the network progressively deteriorated with increasing distance from the stations to about ± 5 km in depth and horizontally. The Figures 6a,b show cross sections of hypocenters along the lines AB and CD shown in Figure 2. The hypocenters of events lying within 4 km from those lines were projected onto the vertical planes.

Vp/Vs ratio and Coda Q value

According to their epicentral location, the seismic events were separated into three main groups in order to carry out an analysis of Vp/Vs variations in the volcanic area (see Figure 2). Events located on the El Aguajito Caldera are referred as to the northeast group. The central group is

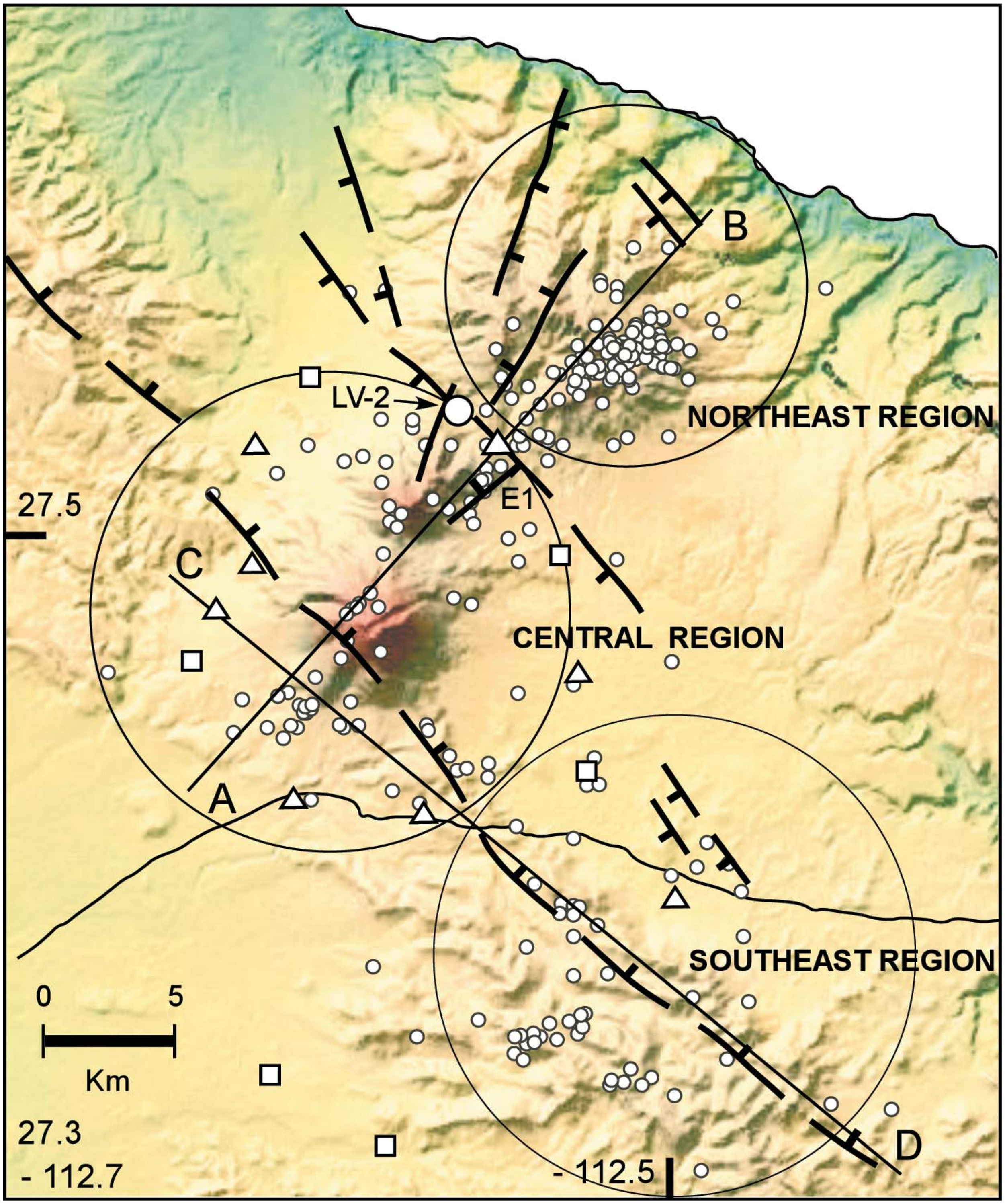

Fig. 2. Map that shows the distribution of digital and analog stations, the located epicenters, and the location of the LV - 2 steam production well. Also shown are the locations of the main groups of events studied (large circles), and the lines AB and CD that mark the position of the vertical planes that show the depth distribution of microearthquakes in Fig. 6.

composed of events located in the Tres Vírgenes volcanic complex (El Viejo, El Azufre and La Virgen volcanoes), while the events located along or near to the La Virgen fault are included in the southeast group. The estimated Vp/Vs values of each group range from 1.68 to 1.76 compared to values of 1.73 to 1.87 which are usually obtained in labora-

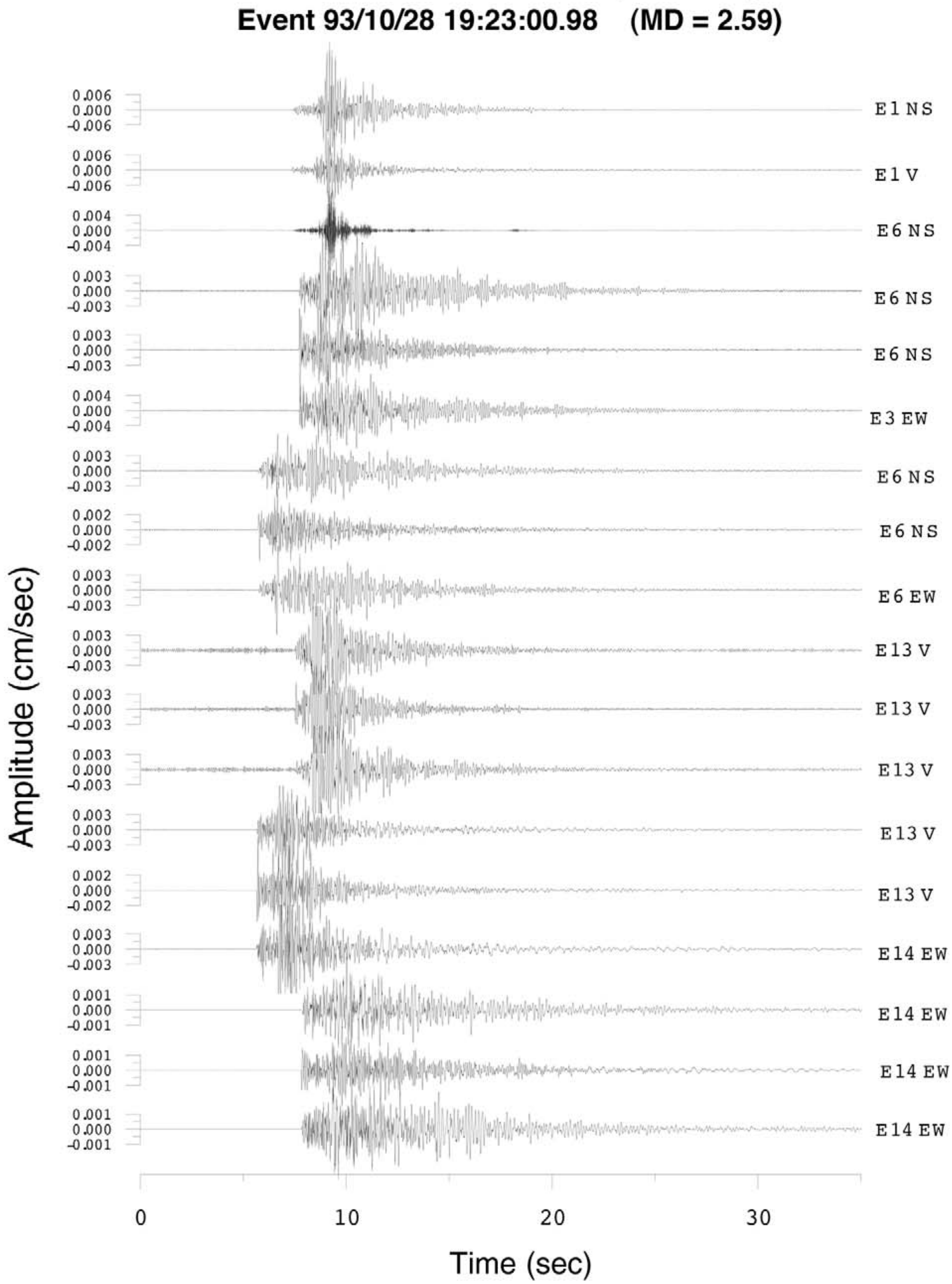

Fig. 3. Example of seismograms recorded by the network for the event of October 28, 1993, 19:23 hr. Units of velocity are cm/sec. V: vertical component, NS: north-south component, and EW: east-west component. The east-west component of the E1 station (E1-EW) did not work properly.

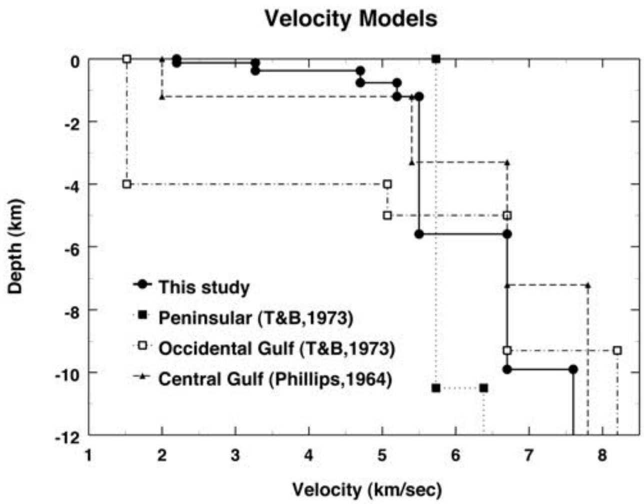

Fig. 4. One-dimensional P-wave velocity model used in this study and the velocity models determined by Thatcher and Brune (1973), and Phillips (1964) for regions close to the Tres Vírgenes volcanic region.

tory and field investigations. These velocity ratios led to a Poisson's ratios from 0.22 to 0.26 compared with values 0.25 to 0.30 which are normally observed. In a series of carefully performed laboratory experiments, Nur and Simmons (1969) noted that dry rocks exhibit low values of Poisson's ratio (<0.20) while saturated rocks show normal to high values (≥0.25). This means that lower than normal poisson's ratio may indicate partial saturation of reservoir rocks.

Figure 5 shows the Vp/Vs values of each epicentral group. In the northeast group (El Aguajito Caldera) the Vp/Vs value is 1.68 (Figure 5b), while in the Central and southeast group (Tres Vírgenes volcanic complex and La Virgen fault) the mean Vp/Vs value is 1.76 (Figures 5c,d). Those variations suggest a heterogeneous structure and lateral variation in the velocities at the volcanic region, mainly toward the northeast region were intense fracturing and hydrotermal activity has been reported (López *et al*., 1995).

On the other hand, Wong (2000) and Wong *et al*. (2001) performed a study of seismic wave attenuation based on the same digital data of this study. They found that the low values of Q_c (Coda Q) obtained from data of station E1 reflect the effects caused by the local geology below that particular station. Furthermore, at this site Wong *et al*. (2001) found an abnormally strong reduction of Q_c at low frequencies (6 Hz), and an attenuation that is three to fourth times larger than for the other station sites. A strong frequency-dependent attenuation is expected to play an important role in areas where the presence of highly fractured rocks, shallow high temperatures, and hydrothermal activity (hot springs and fumaroles) could influence the frequency content of the seismic signals (Gao, 1992). Since these environment conditions prevail around the E1 station, we expect low Q_c values correlated with the dense fracturing, hydrothermal activity and high temperatures that are common around the LV-2 production well. In addition, results from geophysical studies suggest the presence of a highly conductive body below this particular area (Romo *et al*., 2000). Similar results have been reported by Macías (1997) in his study of Coda Q at the Tres Vírgenes volcanic area. This study report low Q_c values in the northeast region, where hydrothermal activity, dense fracturing and high temperatures have been reported by López *et al*. (1995).

FOCAL MECHANISM AND STRESS

Single and composite focal mechanism solutions were calculated from P-wave first motions using Reasenberg and Oppenheimer (1985) programs. Equal area projections of the lower focal hemisphere were used. Single focal mechanism solutions were constrained by at least 6 P-wave first motions. Composite fault plane solution was calculated with events closely related in time and space (Figure 7). The first-motion patterns can be adequately modeled by pure double-couple sources, although the data are not dense enough to exclude the presence of a significant non-double-couple source component. The quality of the focal mechanism solutions varies considerably from moderately to well constrained, depending of the coverage of the focal sphere. As expected, poorly constrained focal solutions were obtained towards the edges of the seismic network. In most cases, the strike of one of the nodal planes matches the lineation of the epicenters. The locations of the estimated focal mechanism are shown in Figure 7. These focal mechanism diagrams are equal-area projections of the lower hemisphere; open circles and triangles denote compressional and dilatational motions, respectively. The P and T on the beach balls denote the position of the P and T axes of deformation. These axes approximate the maximum and minimum compresional stress directions in the region (MacKenzie, 1969).

The estimated composite focal mechanism solutions in this study show strike-slip, normal and oblique faulting; combining strike–slip and dip-slip motion (Figure 7). Most solutions exhibit oblique-slip with normal-dextral motion, so that the average direction of extension is near E-W (Figure 7b). In many cases, the apparent direction of extension is not perpendicular to the average strike of the faults, suggesting a systematic strike-slip component of motion on normal faults. This permits to infer that most of the strike-slip faults moved when both compression and extension were horizontal. On the other side, the variability of the focal mechanisms may reflect spatial inhomogeneities in the stress field or slip on faults of different orientations subjected to a uniform stress field.

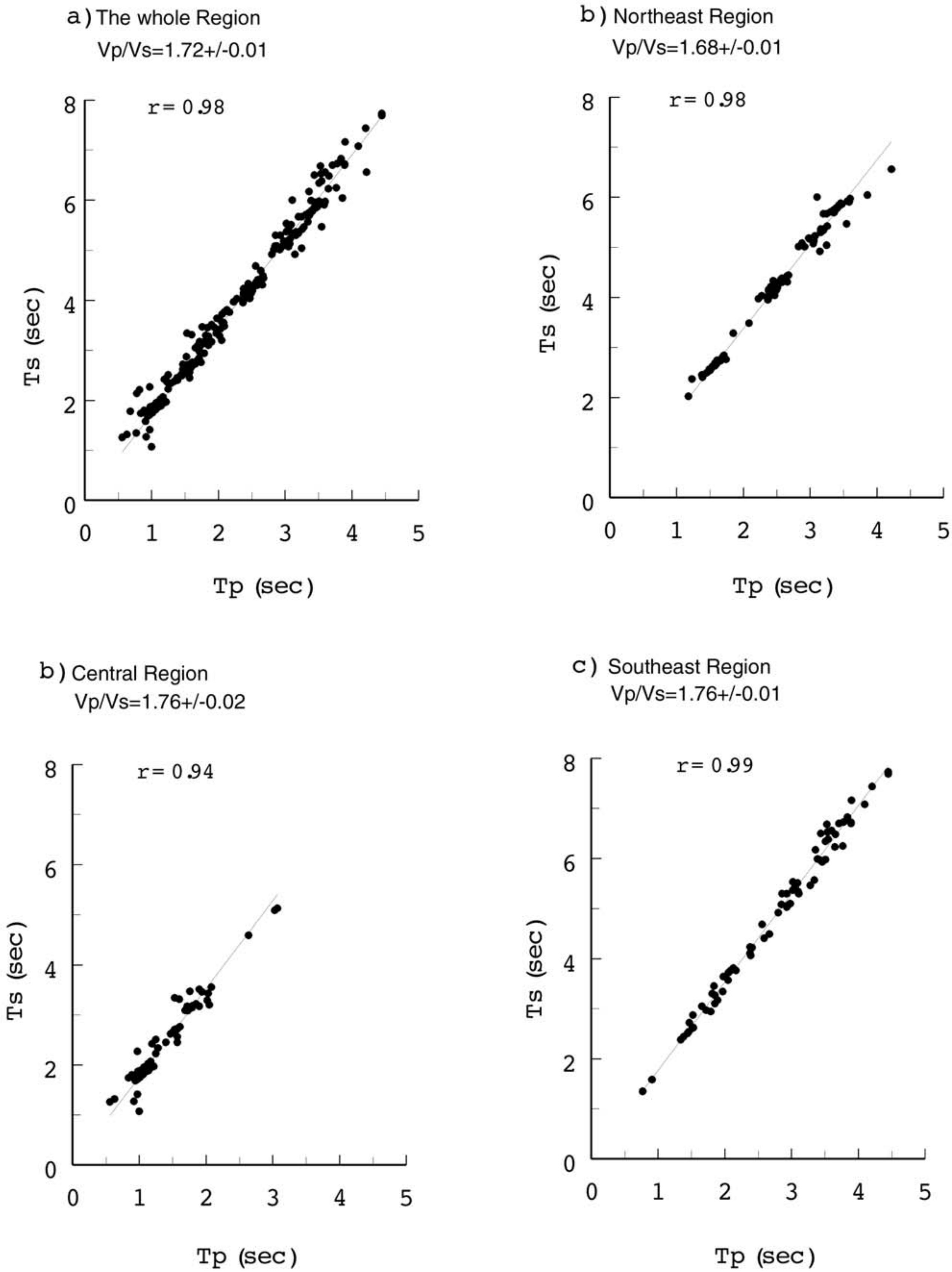

Fig. 5. Vp/Vs values estimated at each earthquake group and for the whole region. Also shown are the correlation coefficients of the linear regression. Earthquake groups are as defined in Fig. 2.

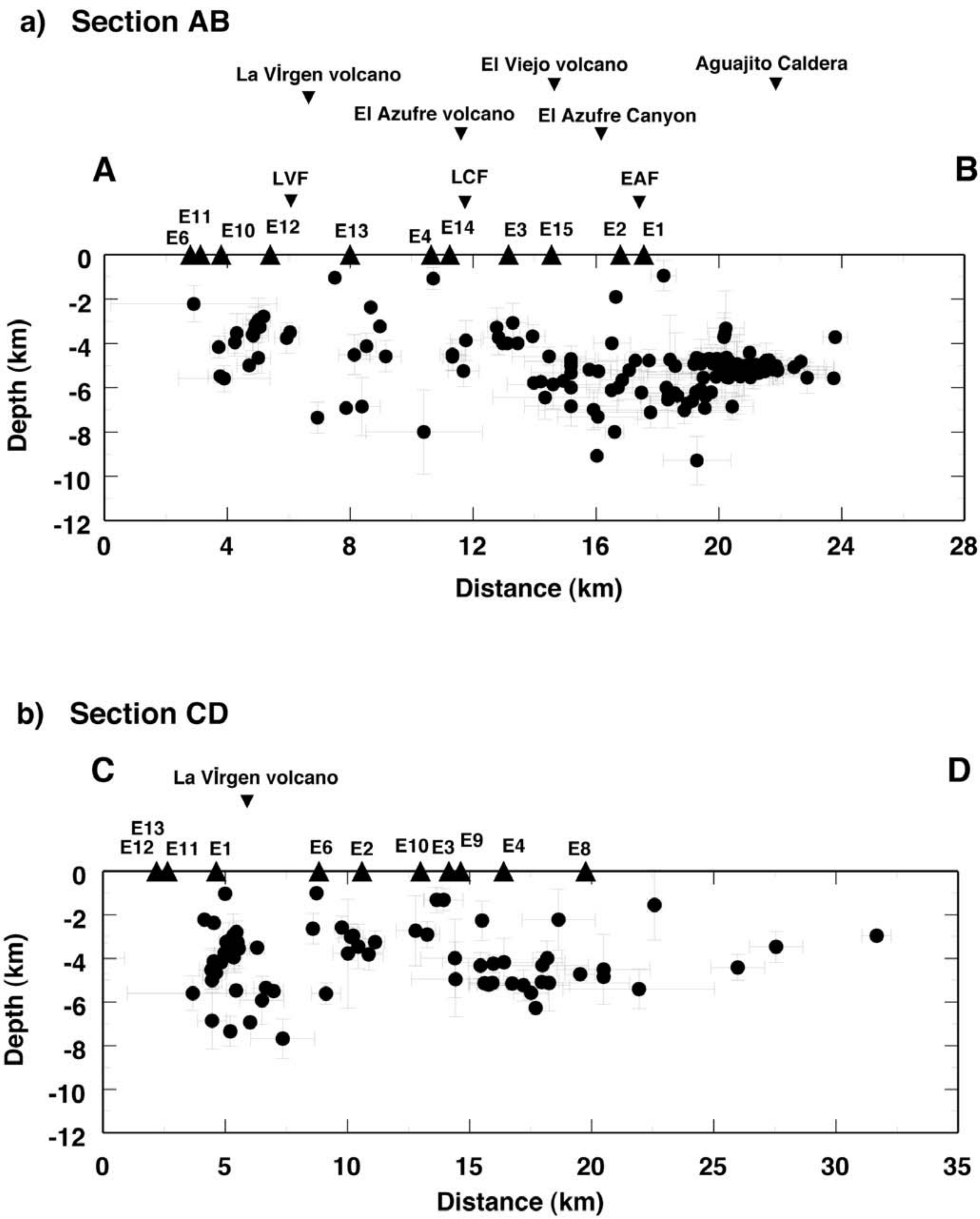

Fig. 6. Depth distributions of the seismic events (solid circles) used in Fig. 2. (a) Section along the volcanic structures showing locations of the microearthquakes lying within 4 km from the line AB. (b) Section along fault strike showing locations of the microearthquakes lying within 4 km from the line CD. Other symbols are as in Fig. 2.

A plot of all P and T axes obtained shows that the tensional axes have an average trend that is nearly horizontal and in the E-W direction (Figure 7b), while the average compressive stress axis is nearly horizontal and in the N-S direction. Although some vertical tensional axes were observed, they are less numerous in comparison to the horizontal ones. Thus we considered that they had much less quantitative importance than the ensuing normal and strike-slip faulting. This stress axes distribution suggest that the tectonic regime at the Tres Vírgenes volcanic region is dominated by a conjugate system of NW-SE dextral strike-slip faults associated with N-S normal faults, maybe in response to the regional tectonic stress imposed by the NW-SE right-lateral strike-slip transform rift system of the Gulf of California.

On the other hand, the state of the stress in the study region is also evident by the northeast-southwest orientation of the Tres Vírgenes volcanic complex and the Aguajito Caldera. The usefulness of aligned volcanic centers in tectonic regional studies was highlighted by Nakamura (1977), who showed that such alignments are perpendicular to the horizontal minimum stress ($\sigma_{h\min}$) which in an active volcanic area must be equal to either σ_3 or σ_2 in order for magmas to reach the surface. This is coincident with the results reported by Umhoefer and Teyssier (1992) at the Tres Vírgenes volcanic region. They considered that the trend defined by the volcanoes of the Tres Vírgenes complex and the Aguajito Caldera could be a consequence of a nearly N-S compresional zone (E-W direction of opening) which, through time, has migrated to the south. They also suggested that the extension may have resulted from dextral strike-slip movements on the Las Víboras-El Azufre and the La Virgen faults, which form a right-stepping offset centered on the Tres Vírgenes complex. In the same way, Sawlan (1981), Garduño-Monroy *et al.* (1993), and López *et al.* (1995) pointed out that the lineament of the major volcanic edifices and the fault geometry at this region indicate that $\sigma_{h\min}$ is essentially E-W.

On the other side, Fabriol *et al.* (1999) carried out a marine geophysical study in the central part of the Gulf of California, between Isla Tortuga and La Reforma Caldera region. Based on backscattering images of the sea floor, they suggested that the onshore and offshore volcanic structures that trend N-S and E-W can be related to more regional tectonic structures, like fracture zone extension, which resulted from the transtensive regime of the Gulf of California transform pull-apart system.

DISCUSSION AND CONCLUSION

The most active area observed in this study was located at the northeast zone, in the Aguajito Caldera (Figure 7). Some events of the microearthquake swarm-like sequence that was recorded during a period of three days were located in this region. This seismic behavior is generally interpreted as indicator of stress heterogeneity. The seismic events of this swarm were concentrated at a 5-km average depth (Figure 6a). Such seismic activity occurred in a zone where SW-dipping normal faults and hydrothermal activity have been reported (López *et al*, 1994). However, a left-lateral strike-slip composite focal mechanism solution with northeast-southwest strike seems to be in agreement with the seismic events located in this zone (Solution 2, Figure 7). Although a unique choice of the fault plane cannot be made from the first motion data, the northeast-southwest striking plane can be chosen due to alignment of the epicenters.

Other active area seems to be the El Cimarrón fault (ECF, Figure 1), the N-S trending left-lateral strike-slip fault that cuts the El Aguajito Caldera in its northwest flank (Garduño-Monroy *et al.*, 1993). Focal depths of the epicenters in this area are concentrated between 5 and 7 km (Figure 6a). The focal mechanism solutions of this sequence show normal motion with a left-lateral strike-slip component, accordingly with the results reported by Garduño-Monroy *et al.* (1993)(Solution 1, Figure 7). They interpreted the general fault pattern as a system of NNW-SSE and NNE-SSW Riedel shears, dextral and sinistral respectively, associated with N-S en-echelon normal faults and extension fractures. Although normal faults with NNE-SSW direction, dominated by sinistral strike-slip, are much less abundant than normal faults with right-lateral strike-slip motion (López *et al.*, 1995). The orientation of this fault pattern seems to be compatible to the stress field associated with the right-lateral faulting related to the opening and evolution of the Gulf of California.

Microearthquakes also occurred in the south portion of the El Aguajito Caldera and along the El Azufre Canyon. This zone, characterized by shallow high temperatures (~200° C) and hydrothermal activity, shows a poorly defined trend of seismic activity. The microearthquake activity in this zone lies at depths between 4 and 7-km (Figure 6a). The focal mechanisms show predominantly strike-slip and oblique-slip faulting (Solutions: 3, 14, and 15, Figure 7). Candidate planes of the fault plane solution 15 seem to be rotated from those shown for the nearby solutions 3 and 14. The latter solutions feature more strike-slip than dip-slip faulting. The strike-slip focal mechanism solutions estimated in this area seem to be associated with the NE-SW trending La Puerta fault and the south-oriented extension of the Las Víboras fault in the vicinity of the LV-2 well, respectively. This particular region consists of many fault structures with dominantly strike-slip motion and steeply-dipping planes, implying possible dextral movement on normal faults (Umhoefer and Teyssier, 1992; López *et al.*, 1995).

a)

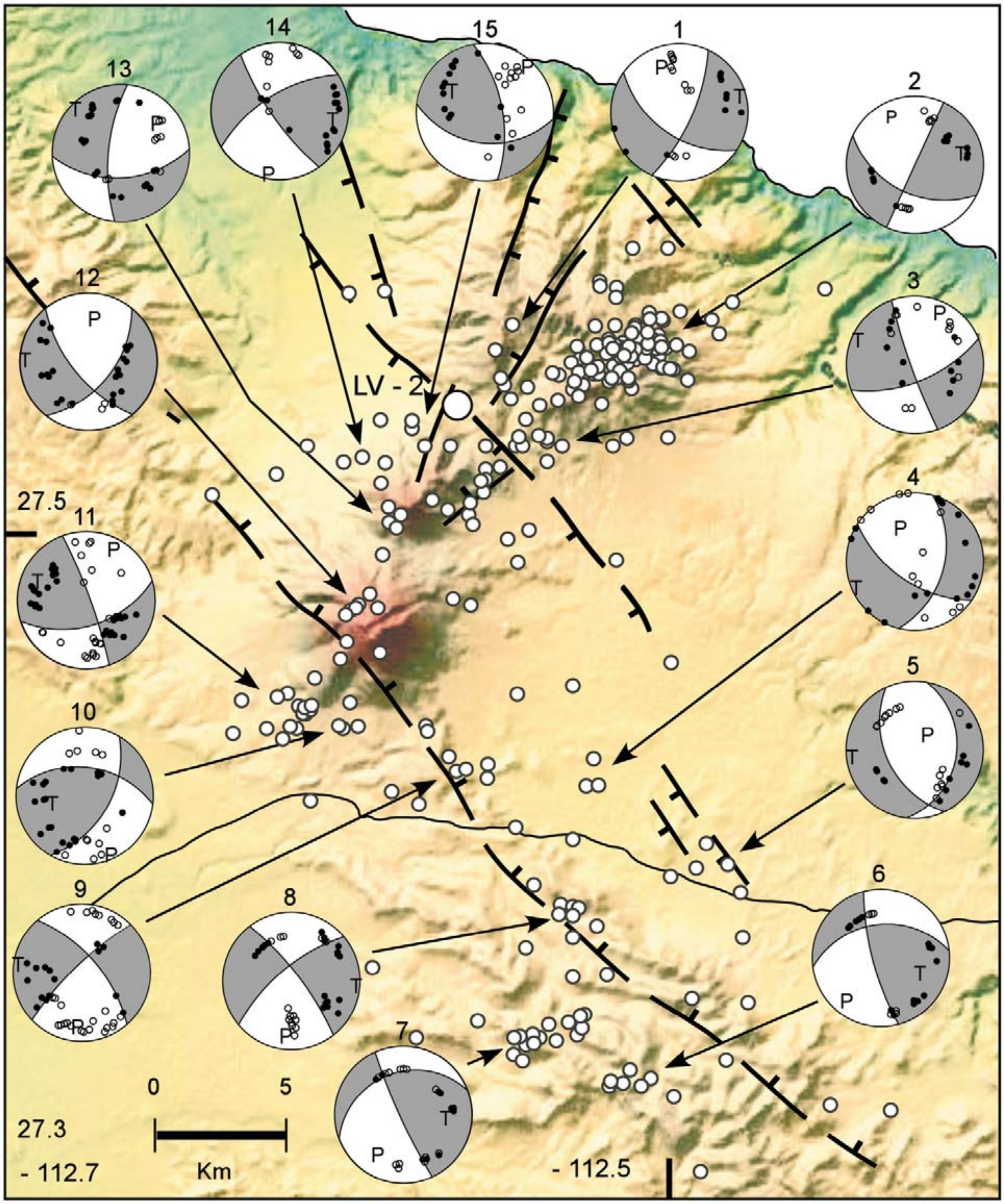

Fig. 7. (a) Map showing some composite focal mechanisms (lower-hemisphere, equal-area projection) connected by an arrow to their corresponding group of epicenters. Shaded and open areas indicate compression and dilatation, respectively.

From Figures 6a and 6b, we can see that some seismic events occur directly beneath the Tres Vírgenes volcanic complex. Most of the microearthquakes are concentrated between 3- and 7-km depths, with some scattered events located at depths from 1 to 8 km (Figure 6a). Mib)

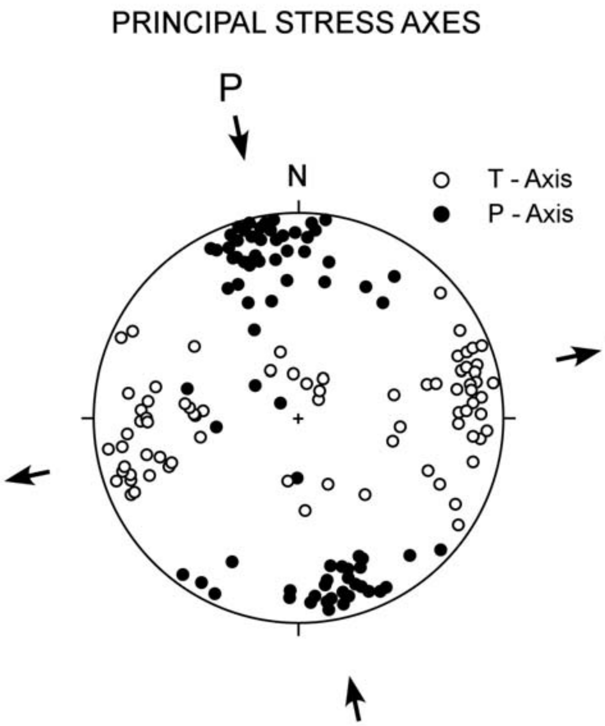

Fig. 7. (b) P- and T-axes distribution on the equatorial plane of an equal-area projection of the lower hemisphere of the focal sphere. The solid arrows indicate average directions of the maximum (P) and minimum (T) compresional stresses at the Tres Vírgenes volcanic region.

croearthquakes of the volcanic structures were located within the igneous basement, beneath the volcanic overlaying. Focal mechanism solutions for these events show predominantly oblique-normal faulting (Solutions: 12 and 13, Figure 7), suggesting extensional faulting beneath the volcanic alignments. The seismic events that were located in the south-southwest flank of the Tres Vírgenes volcano show mainly strike-slip faulting with some component of normal motion (Solutions: 11 and 10, Figure 7). The candidate planes for the apparent oblique-reverse mechanism (solution 10, Figure 7) seem to be rotated from those shown by solutions of nearby events (Solutions: 9 and 12, Figure 7). The apparent rotation of the fault planes may reflect local changes in the stress field, or slip on faults of different orientations under a uniform stress field. On the other hand, Angelier *et al.* (1981) suggested that reverse faults in the area could be related to fault motions on originally normal faults that have been subsequently rotated by block tilting, due to more recent normal faulting.

The seismic activity recorded to the south-southeast of La Virgen volcano seems to be associated with the northwest-southeast trending dextral-normal La Virgen fault described by López *et al.* (1995). The trace of this fault coincides with the southern Main Gulf Escarpment, which has been generally interpreted as the boundary between the Gulf Extensional Province and the topographically higher Peninsular Basin and Range (Gastil *et al.*, 1975). Small concentrations of epicenters show an apparent lineament along the La Virgen fault, except for a few clusters and some isolated events that seem to be parallel or nearly parallel to the trace of this fault. This activity occurred at depths from near the surface to about 8-km. Most of these events are concentrated at depths between 3 and 7 km (Figure 6b). Focal mechanism solutions for these seismic events show strike-slip, oblique-normal and oblique-reverse fault type. In contrast, normal fault type is prominent at the La Virgen valley, about 5 km eastward from the La Virgen fault. The strike-slip and the apparent oblique-reverse focal mechanisms seem to be related to local variability in fault orientations of the La Virgen fault. Similarly, the oblique-normal fault plane solutions at La Virgen valley seem to be related with the NW-SE trending normal faults located in the area, although more definitive data are necessary to define the mode of faulting of the seismicity at this area.

On the other side, the variation of the Vp/Vs ratio at each epicentral group suggests a heterogeneous velocity structure and lateral variation in the volcanic region, mainly toward the northeast region, were hydrotermal activity has been found. Similarly, low values of Q_c are expected around the E1 station, where dense fracturing, hydrothermal activity and high temperatures are commonly observed. Also, we noticed that the seismic waves propagating through this area were conspicuosly attenuated. This fact suggests that a high-temperature, ductile, and low-Q body may exist under the El Azufre Canyon. The tectonic regional framework, combined with the local stress field and the high thermal gradient in the Las Tres Vírgenes volcanic area, may produce a higher proportion of small magnitude local events in comparison with events of higher magnitude that are characteristic of the Gulf of California.

The directions of the principal stress axes estimated in this study are consistent with the tectonic framework found at the Santa Rosalia Basin, about 15-20 km south of La Virgen volcano, where a mean E-W to ENE-WNW near-horizontal tensional stress predominantes. The averaged N-S and E-W orientation of the principal stresses estimated here suggest that the tectonic regimen of the Tres Vírgenes volcanic region is dominated by a conjugate system of NW-SE dextral strike-slip to oblique-slip faults associated with N-S normal faults with dip-slip motions. This occurs probably in response to the regional tectonic stress imposed by the NW-SE right-lateral strike-slip transform fault system in the Gulf of California.

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