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The Aztlán Fault System: control on the emplacement of the Chichinautzin Range volcanism, southern Mexico Basin, Mexico. Seismic and gravity characterization

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Abstract

Gravity and seismic studies enabled us to establish the major features of the shallow crustal structure beneath Chichinautzin Range. Accordingly, the Chichinautzin Range evolved above Mesozoic calcareous rocks lying on a metamorphic basement. To the north and south this basement is downfaulted. Nevertheless the north dipping faults downward displace the basement to larger depths (2 to 3 km) in the Mexico and Toluca basins. In the Morelos Basin, the basin is shallower. As block-faulting evolved, the basement edge migrated southwards, thus widening an E-W oriented major depression south of the Mexico Basin. In particular, gravity modeling enabled us to integrate the different faults mapped up to today in and around the Chichinautzin Range into a fault system that can be correlated from the Nevado de Toluca. This system will be referred to collectively as the Aztlán Fault System.

The Xicomulco, Aztec (central and major fault) and La Pera faults are featured by seismicity. Orientation and dips obtained from simple and composite mechanisms indicate NW-SE to N-S extension with minor E-W left-lateral movement. In particular, seismicity extends down to the brittle-ductile transition crustal zone (maximum hypocentral depths of about 15 km) but consequently the major faults, considering their length, should reach lower crustal levels (approximately 40 km). This system is a major active fault system of at least 100 km in length and 30 – 40 km in width, with a density of approximately 10 E-W faults in 30 km, and local extension of about 10 %.

In conjunction with pre-existing NW-SE and NE-SW faults, this E-W fault system would have intensely fractured the crust beneath the Sierra de Chichinautzin. This high degree of fracturing would have enabled the relatively fast emplacement of large quantities of volcanic material to give rise to the Chichinautzin Range, closing the Mexico Basin to the south. The gravity model shows how the different styles of structures north and south of the Chichinautzin Range (extensional and compressive) accommodate themselves. In particular, faults of the Taxco-San Miguel de Allende system affect the basement of the Morelos Basin well further south.

Keywords: Chichinautzin Range, Mexico Basin, Aztlán Fault System, control of magma emplacementl, seismicity, shallow crustal model.

Resumen

Estudios gravimétricos y sísmicos nos permitieron establecer las características mayores de la estructura cortical somera por debajo de la Sierra de Chichinautzin. La Sierra de Chichinautzin evolucionó sobre rocas calcáreas mesozoicas descansando sobre un basamento metamórfico. Hacia el norte y el sur este basamento se encuentra fallado. En las cuencas de Toluca y de México, sin embargo, las fallas que buzan al norte desplazan el basamento a mayores profundidades (2 a 3 km). En la Plataforma de Morelos, la *depresión es más somera. Conforme el fallamiento evolucionó, el extremo del basamento migró hacia el sur, haciendo más ancha una depresión E-W localizada al sur de la Cuenca de México. En particular, la modelación gravimétrica nos permite integrar las diferentes fallas estudiadas hasta la fecha en la Sierra de Chichinautzin y sus alrededores en un sistema de fallas que puede ser correlacionado desde el volcán Nevado de Toluca. Este sistema será denominado colectivamente el sistema de fallas Aztlán. Las fallas Xicomulco, Azteca (la falla mayor y central) y La Pera están caracterizadas por sismicidad. Las orientaciones y echados obtenidos de mecanismos compuestos y simples indican una extensión NW-SE a N-S con una componente menor lateral izquierda E-W. En particular, la sismicidad alcanza la zona cortical de transición frágil-dúctil (máximas profundidades hipocentrales de 15 km), y consecuentemente las fallas mayores, de acuerdo a su longitud, deberían alcanzar niveles de la corteza inferior (alrededor de 40 km). Este sistema es un sistema mayor activo de por lo menos 100 km de longitud, y con un ancho entre 30 y 40 km, con una densidad de 10 fallas E-W en 30 km, y un extensión local del 10 %.*

Junto con fallas preexistentes NW-SE y NE-SW, este sistema de fallas E-W habría fracturado intensamente la corteza debajo de la Sierra Chichinautzin. Este fracturamiento mayor habría permitido el relativamente rápido emplazamiento de grandes cantidades de material volcánico que dio origen a la Sierra Chichinautzin la cual cerró la Cuenca de México por el sur. El modelo gravimétrico muestra la coexistencia de diferentes estilos de estructuras al norte y al sur de la Sierra Chichinautzin (de naturaleza extensional y compresiva). En particular, más al sur, fallas del sistema Taxco-San Miguel de Allende afectan el basamento de la Cuenca de Morelos.

Palabras clave: Sierra de Chichinautzin, Cuenca de México, Sistema de Falla Aztlán, control del emplazamiento del volcanismo, sismicidad, modelo cortical somero.

1. Introduction

The Trans-Mexican Volcanic Belt (TMVB) is a Pliocene-Quaternary elongated volcanic province, approximately between the latitudes 19.5° and 21° N, spanning from the Pacific Ocean to the Gulf of Mexico (Figure 1). The most active dacitic-andesitic stratovolcanoes in Mexico are located in it. Also included are cinder cone fields, isolated occurrences of rhyolitic volcanism, large silicic caldera centers, and plateau lava sequences (Mooser, 1972; Demant, 1978, 1981a, 1981b; Negendank *et al.*, 1985; Ferriz and Mahood, 1986; Ferrari *et al.*, 2012). It is currently associated with plate subduction processes along the Middle America Trench (MAT). The non-parallel position of this volcanic arc, with respect to MAT, is associated with the oblique convergence of the Cocos plate. Several geophysical, geological and geochemical aspects cannot be fully accounted for by subduction, so other models have been proposed: mantle plume (OIB-type magmas) (Márquez *et al.*, 1999a), an extensional tectonic setting (*i.e.*, rifting) (Sheth *et al.*, 2000, 2002; Verma, 2002; Velasco-Tapia and Verma, 2013), and propagation of a lithospheric tear (Ferrari, 2004; Ferrari *et al.*, 2012).

Demant (1978, 1981a, 1981b) defined five major sectors along the TMVB: 1) at its western end, the Chapala-Tepic graben (which includes several large stratovolcanoes); 2) the Colima graben; 3) the Michoacán-Guanajuato cinder cone field; 4) the valleys of Toluca, Mexico, and Puebla (dominated by high stratovolcanoes around large lacustrine valleys), including an extensive monogenetic field called the Chichinautzin Range that delimits the Mexico Basin to the south; and 5) the eastern TMVB, including the N-S Pico de Orizaba-Cofre de Perote range (Robin, 1982) that extends down to the Gulf of Mexico coast (Negendank *et al.*, 1985). In general, the TMVB occupies several depressions (Figure 1).

In the central part of the TMVB it has been assumed that the large basins of Toluca, Mexico, and Puebla are limited by major intracortical faults (Venegas-Salgado *et al.*, 1985; Pérez-Cruz, 1988; Silva-Romo *et al.*, 2002; Siebe *et al.*, 2004a). Several studies have focused on the study of these faults in the Mexico Basin (Campos-Enríquez *et al.*, 1997; Huizar-Álvarez *et al.*, 1997; Campos-Enríquez *et al.*, 2000; Campos-Enríquez *et al.*, 2002; García-Palomo *et al.*, 2002a).

From a tectonic point of view, Pasquaré *et al.* (1987) subdivided the TMVB into three sectors. The western one comprises the Tepic-Zacoalco graben. The central one includes the Chapala-Tepic and Colima grabens, and the E-W Chapala-Maravatio depression. This sector is featured by E-W to NE-SW regional depressions. Contrastingly, the eastern sector is featured by N-S, NW-SE, and NE-SW faults. These two last sectors are separated by the Taxco-San Miguel de Allende Fault System (TSMAFS). Ferrari *et al.* (2012) includes as a fourth sector the easternmost TMVB. Another important tectonic element is the Jalisco Block limited to the north by the Tepic-Zacoalco graben and to the east by the Colima graben (*i.e.*, Allan *et al.*, 1991).

It has been proposed that the southern limit of the TMVB south of the Mexico Basin corresponds to an E-W fault. To account for the large height difference between the Mesozoic calcareous rocks in the valley of Mexico City (at depths between 1200 and 3775 m) and to the south of it (about 1500 m.a.s.l.), it was assumed that the Chichinautzin Range was emplaced along a regional normal fault (*i.e.*, Delgado-Granados *et al.*, 1995, 1997; Márquez *et al.*, 1999b; Ferrari *et al.*, 2002). Along this fault, the Mexico Basin should be displaced downward. Also, alignments of more than 15 cinder cones on the Chichinautzin Range led to infer the

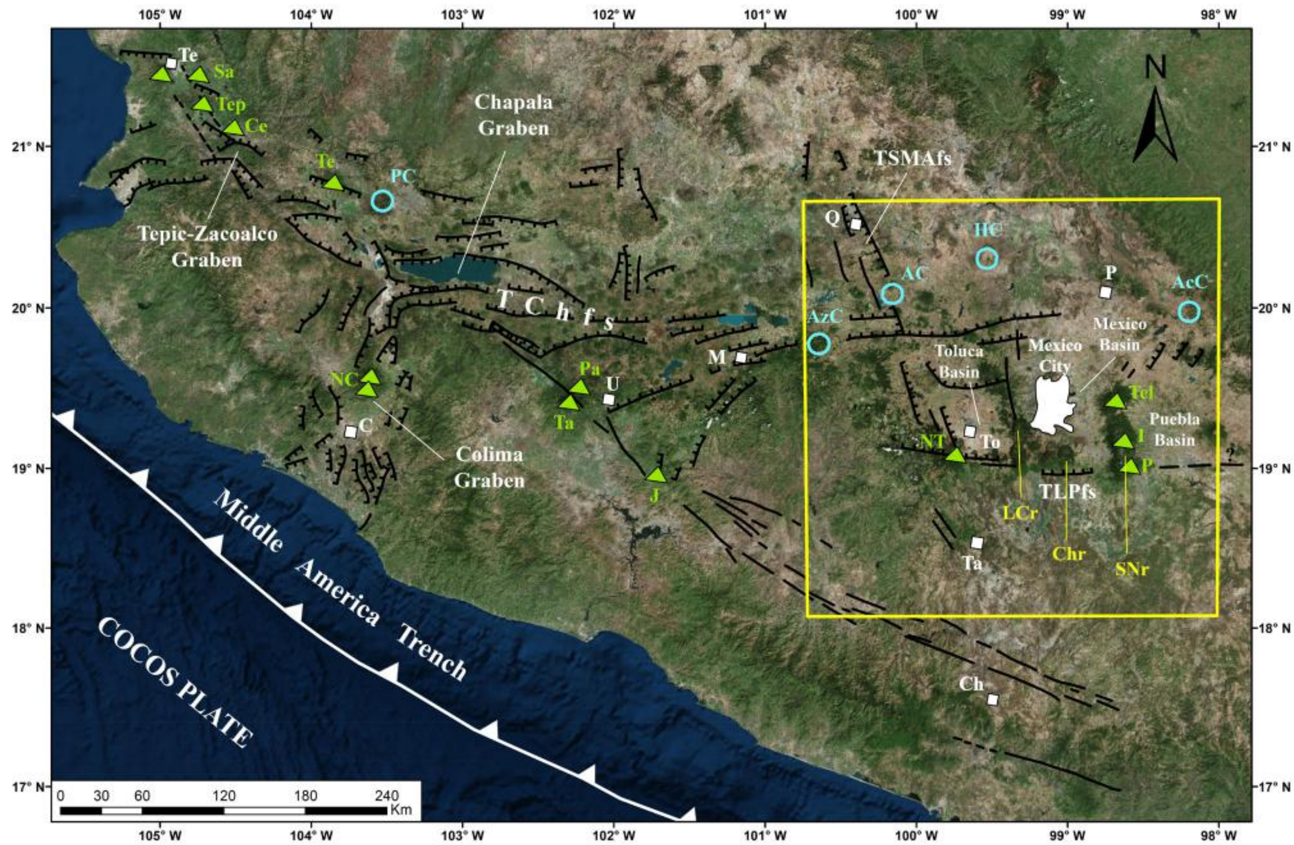

Figure 1. The study area in the context of southern Mexico after Johnson and Harrison (1989). Location of major volcanic centers and main structural systems are indicated. Ch: Chichinautzin Range, LC: Sierra de Las Cruces, SN: Sierra Nevada, Iz: Iztaccihuatl, Pp: Popocatepetl, TSMAFS: Taxco-San Miguel de Allende Fault System.

existence of a major E-W fault along the Chichinautzin Complex (Márquez *et al.*, 1999b).

According to Alaniz-Álvarez and Nieto-Samaniego (2005), from the Miocene to the Recent the TMVB has been the site of deformation, and since the Eocene the TMVB acted as a frontier or zone coupling the tectonic events taking place to the north and south of it. In particular, they postulated the existence of a major fault system (named La Pera) that during the Oligocene-Miocene accommodated deformation by N-S or NNW extension.

As mentioned, the existence of the La Pera Fault was hypothesized based on the arguments already summarized, but no formal study of it has been reported. As we will see below, several faults have been mapped to the north and south of, and within the Chichinautzin Range (Figure 2). More recently, the Tenango Fault System, located immediately to the west, has been related to La Pera Fault (*i.e.*, García-Palomo *et al.*, 2000, 2008; Norini *et al.*, 2006). Norini *et al.* (2006) established its morphologic expression as well as its kinematics.

Here, based on the inference by Campos-Enríquez *et al.* (2000) of a north dipping fault delimiting the Basin of Mexico in the south, we establish the crustal structure of the Chichinautzin Range focused on faults affecting it. This study enabled us to establish a relationship between the previously mapped faults.

This gravity modeling enabled us to confirm the existence of a major crustal north-dipping fault delimiting Mexico Basin to the south (*i.e.* delimiting to the north the Chichinautzin Range) as originally inferred by Campos-Enríquez *et al.* (2000). Additionally, this model enabled us to infer that the already mapped faults are subordinate to this major crustal structure. Several of these faults were characterized seismically. In view that the originally proposed La Pera Fault is subordinate to the major north-dipping faults inferred by Campos-Enríquez *et al.* (2000), in this study all these faults will be referred collectively to as the Aztlán Fault System.

In this context, this study has as objectives: a) to analyze the local seismicity observed along the northern limit of the Chichinautzin Range, in the zones close to the towns of Xochitepec and Milpa Alta, as well as the seismicity in the southwestern part of the range, and b) to interpret a N-S gravity profile, from the western Chichinautzin Range southwards into the neighboring Morelos Basin.

2. Geological setting

The Chichinautzin Range consists of a conspicuous concentration of Quaternary monogenetic volcanoes mainly to the south of the Mexico Basin (de Cserna *et al.*, 1988). This monogenetic volcanism, mainly of the Strombolian type, closes the Mexico Basin to the south. The sequence of lavas and tephras of this range were considered as the Chichinautzin Group by Fries (1960). As Bloomfield (1975) and Martin del Pozzo (1982) succeeded in establishing the separation between its different members, this volcanic sequence became the Chichinautzin Formation. Lavas comprise blocky andesites, with some dacites and basalts (Martin del Pozzo, 1982). Verma (2000) reported hy-normative mafic rocks. According to the combined geochemical and isotopic data, he concluded that there is a lack of evidence to associate the origin of these rocks to subduction of the Cocos plate. He proposed that they probably were generated in a rifting tectonic setting. More recently, Velasco-Tapia and Verma (2013) described more cases of mafic rocks, distributed along 99° 10′ longitude, with affinity to an extensional tectonic setting. Also Arce *et al.* (2013) reported more cases on this significant compositional heterogeneity.

The normal geomagnetic polarities of these rocks constrain its age to less than 700000 years (Mooser *et al.*, 1974). Initial reported radiometric dates range from 9.4 to 2.4 ky (Bloomfield, 1975; Arnold and Libby, 1951), bracketing its age between Late Pleistocene and Holocene. Siebe *et al.* (2004b) recently fixed the age of the most recent activity of this monogenetic field at 1675 +/- 35 years BP. To the east and west it is limited by Paleogene volcanic rocks, and lies discordantly on volcanic products of a similar age (Martin del Pozzo, 1982; de Cserna *et al.*, 1988).

A K-Ar age of 0.39 Ma has been reported for the andesitic Ajusco volcano (Mora-Álvarez *et al.*, 1991). For the main Chichinautzin eruptive period Velasco-Tapia and Verma (2013) reported ^{14}C dates of less than 40 ka. Arce *et al.* (2013) presented additional geochronologic dates older than 1 Ma, which indicate that the magmatic activity started much prior to 40000 years as previously reported (Bloomfield, 1975; García-Palomo *et al.*, 2002b; Siebe *et al.*, 2004b), and probably was of an episodic nature at 0.8, 0.2, and 0.08 Ma. Thus, its initial stage was coeval with the southern Sierra de Las Cruces volcanism which has been bracketed between 3.6 and 1.8 Ma (Osete *et al.*, 2000). The activity of Zempoala volcano has been dated at 0.7 Ma, and that of La Corona volcano at 1.0 Ma (*i.e.*, Arce *et al.*, 2013). Fries (1960) estimated its thickness at 1,800 m, which represents an upper limit. Estimates based on subsurface data are similar (*i.e.*, Alaniz-Álvarez and Nieto-Samaniego, 2005).

More than 200 monogenetic structures have been mapped (*i.e.*, scoria cones, lava cones and fissural lava flows) (Martin del Pozzo, 1982). The general E-W trend of these structures has been noted by several authors (*i.e.*, Fries, 1960; Demant, 1978; de Cserna *et al.*, 1988; Martin del Pozzo, 1989; Vázquez-Sánchez and Jaimes-Palomera, 1989; Mooser *et al.*, 1996). Márquez *et al.* (1999b) established quantitatively that volcanic cones are oriented E-W, but also present subordinate NE-SW and NW-SE orientations. As already mentioned, several faults and cone lineaments had already been reported inside the Chichinautzin Range, as well as in its vicinity (*i.e.*, the Tenango Fault by Bloomfield and Valastro, 1974; Vázquez-Sánchez and Jaimes-Palomera, 1989).

Concerning the southern limit of the Chichinautzin Range, Delgado-Granados *et al.* (1995), to account for the large height difference between the Chichinautzin Range and the Morelos Basin, proposed a south dipping fault system delimiting to the south the Chichinautzin Range. Lermo *et al.* (1995) also reported seismological evidence supporting the existence of such a fault. Delgado-Granados *et al.* (1997) presented morphological, structural, seismological and gravimetric evidence of the existence of La Pera Fault. Campos-Enríquez *et al.* (1999) elaborated the first gravity model of the Mexico Basin–Morelos Platform transition. Additional geologic evidence was reported by Delgado-Granados *et al.* (1999).

New faults were reported within the Chichinautzin Range (*i.e.*, Ávila-Bravo, 1998; García-Palomo *et al.*, 2008). Detailed studies were undertaken on known faults. In particular, the Tenango Fault System was morphologically and kinematically characterized by Norini *et al.* (2006). Even if not completely characterized all these faults have been considered, together with assumed faults, as comprising a fault system (up to now named La Pera Fault System). Accordingly, this hypothesized fault system can be traced from south of Nevado de Toluca volcano, through the Chichinautzin Range.

In the following, we summarize the major faults and lineaments known up to the present around the Chichinautzin Range. We will proceed from west to east (Figure 2, Table 1).

1. The Tenango (1), Joquicingo (2), and San Pedro (3) faults were reported by Bloomfield and Valastro (1974). They were also mapped and reported by several authors (*i.e.*, Vázquez-Sánchez and Jaimes-Palomera, 1989; Márquez *et al.*, 1999b). García-Palomo *et al.* (2000) and Norini *et al.* (2006) studied the kinematic of these and associated faults (*i.e.*, the Tenango Fault System).
2. Faulting of the southern Sierra de Las Cruces was studied by García-Palomo *et al.* (2008). In particular, in the southernmost sector, two approximately E-W minor faults are reported. One fault is south (4) of El Ajusco volcano on the valley side slope. The other fault (5) is about 5 km to the south (between La Corona and Zempoala volcanoes).
3. Within the Chichinautzin Range García-Palomo *et al.* (2008) mapped an E-W, south-dipping fault

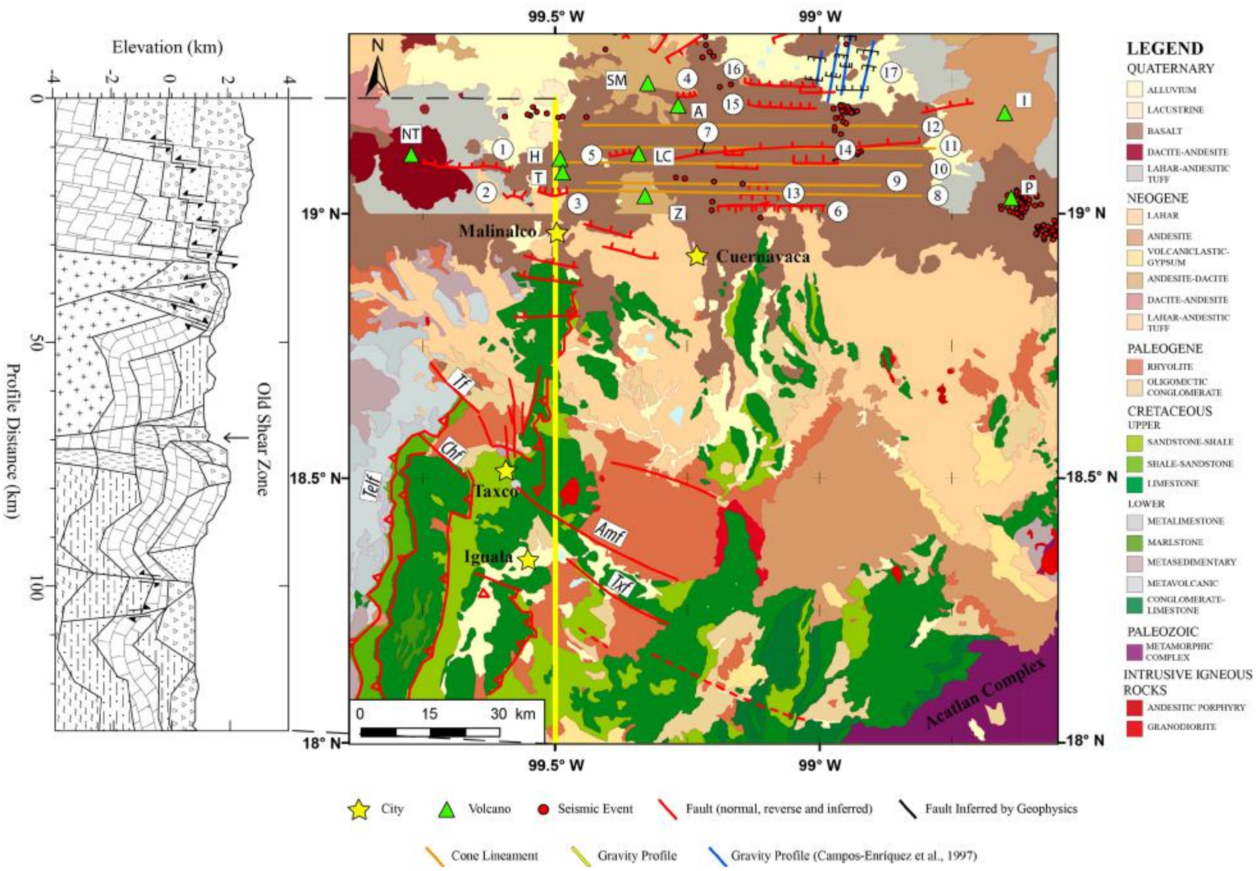

Figure 2. Detailed study area. Geologic background after the mining and geologic maps E-14-4 and F-14-2 of the Servicio Geológico Mexicano (Rivera-Carranza *et al.*, 1998; De la Teja-Segura *et al.*, 2002). In map F-14-2 no differentiation of the volcanic products of Nevado de Toluca was made. Left: the gravity model along the meridian 99° 30' W, at same scale for comparative purposes. Right: Location of major volcanic and tectonic structures. Brown lines represent lineaments inferred by Márquez *et al.* (1999) (see Table 1). Key to gravity model is indicated in Figure 4. Summary of faults is given in Table 1. NT: Nevado de Toluca, LC: La Corona Volcano, SM: San Miguel Volcano, A: Ajusco Volcano, P: Popocatepetl Volcano, I: Iztaccihuatl Volcano. H: Holotepec Volcano, Z: Zempoala, T: Tenango. Telf: Teloloapan thrust Fault (*i.e.*, Cabral-Cano, 2000a, b). Chf: Chichila Fault (Alaniz-Álvarez *et al.*, 2002). Tf: Tetipac Fault (Alaniz-Álvarez *et al.*, 2002). Txf: Tuxpan F, Amf: Los Amates Fault (*i.e.,* Morán-Zenteno *et al.*, 2005).

Table 1. Mean features of faults and lineaments discussed in the text.

Fault (Number)	Name	Studies	Type	Dip	Length (km)	Seismic Activity
1	Tenango Fault	a, b	Normal, Left lateral	north	17	Not reported
2	Joquicingo Fault	a, b	Normal	north	3.5	Not reported
3	San Pedro Fault	a, b	Normal	north	5.7	Not reported
4	Ajusco	c	Normal	north	4	Not reported
5	LaCorona	c	Normal	north	5.3	Not reported
6	La Pera Fault	c	Normal	south	21.1	Not reported
7	Cinder cone alignment	d	-	-	49.3	Not reported
8 - 12	Cinder cone alignment	e	-	-	-	Not reported
13	La Pera Fault System	f	Normal	north and south	-	yes
14	Major Fault System (Aztec Fault)	g	Normal	north	8.7	yes
15	Xochimilco Fault	c	Normal	north	13.5	yes
16	Xicomulco Fault	c	Normal	north	14.2	
17	E-W Chalco sub-basin Fault System	h	Normal	north and south	-	yes

where the Chichinautzin southward topographic slope begins, and called it La Pera Fault (6).

4. Vázquez-Sánchez and Jaimes-Palomera (1989) reported cinder cones along a fault (in Figure 2 fault number 7). Also the E-W cinder cone alignments of Márquez *et al.* (1999b) are indicated (8-12). The central one is referred to as lineament number 8.
5. On the southern slope of the western Chichinautzin Range, Ávila-Bravo (1998) mapped several south-dipping, E-W faults based on cinder cone alignments as well as the tectonic tilting observed in the blocks delimited by these faults. She called these local faults the La Pera Fault System (13).
6. Campos-Enríquez *et al.* (2000), as already mentioned, found that to the south, the basin is delimited by north dipping normal faults (14). One of these faults correlates with the central alignment of Márquez *et al.* (1999b) (14).
7. On the slope to the Mexico Basin, García-Palomo *et al.* (2008) mapped the parallel E-W, north-dipping Xochimilco, and Xicomulco faults (15 and 16) up to the foothills of Sierra de Las Cruces.
8. At a local scale, Campos-Enríquez *et al.* (1997) established the existence of shallow E-W trending faults conforming graben and half-graben type structures in the Chalco sub-basin (17), where previously Vázquez-Sánchez and Jaimes-Palomera (1989) proposed the existence of a graben.

Different stress regimes are observed to the north and south of the Trans-Mexican Volcanic Belt. At the end of the Cretaceous, the Laramide orogeny associated with a compressive tectonic regime, gave rise to N-S and E-dipping folds in the Morelos Platform (Alaniz-Álvarez and Nieto-Samaniego, 2005). Also W-dipping folds are observed at the western and eastern limits of this platform. Already during the Eocene, north of the TMVB, there was an extensional regime, while southern Mexico was affected by transcurrent tectonics. In the Oligocene, north of the TMVB, there was N-S and E-W extension, while in southern Mexico lateral faults gave rise to NE-SW extension and NW-SE contraction (Alaniz-Álvarez and Nieto-Samaniego, 2005). From the Miocene to the Recent, deformation is concentrated in the TMVB, which is characterized by NW-SE to N-S extension and minor E-W left-lateral transcurrent movement (Alaniz-Álvarez and Nieto-Samaniego, 2005).

Neotectonics in the TMVB is featured by extension, mainly in its western and central portions with a minor left-lateral component, which is absent in its eastern part (Suter *et al.*, 2001a, 2001b).

Establishment of the structure of the Aztlán Fault system can enable us to see how the different tectonic styles are accommodated.

3. Previous gravity studies

Regional gravity studies have focused partially on the study area (Molina-Garza and Urrutia-Fucugauchi, 1993; Campos-Enríquez and Garduño-Monroy, 1995; Urrutia-Fucugauchi and Flores-Ruiz, 1996; Campos-Enríquez and Sánchez-Zamora, 2000).

Molina-Garza and Urrutia-Fucugauchi (1993) and Urrutia-Fucugauchi and Flores-Ruiz (1996) focused on the long wavelength crustal-thickness variations beneath Central Mexico.

Constrained by seismological data, Campos-Enríquez and Garduño-Monroy (1995) modeled crustal intermediate wavelength details along a transect from the Pacific Ocean to the Gulf of Mexico. Beneath Cuitzeo Lake, they inferred a crustal thickness of about 35 km. Furthermore, based on the regional pattern of the Bouguer anomaly (*i.e.*, Tanner *et al.*, 1988) they inferred that the Tepic-Chapala rift and its eastern extension, the Chapala-Queretaro depression, are featured by crustal thinning in correspondence with extensional tectonics affecting this western sector of the TMVB.

Campos-Enríquez and Sánchez-Zamora (2000) established a normal thickness for the crust in the eastern sector (45 km below the Mexico Basin). Campos-Enríquez and Sánchez-Zamora (2000) included the Mexico Basin in their regional model, with major faults bounding this tectonic depression to the north and south. This constitutes the first antecedent of a normal fault bounded depression. These studies were based on smoothed, regional versions of the gravity field in central México (*i.e.*, Monges-Caldera and Mena-Jara, 1973; Tanner *et al.*, 1988; De la Fuente *et al.*, 1991). These gravity data sets are based on the pioneer gravity work conducted in Mexico by Monges-Caldera and Mena-Jara (1973).

4. Gravity studies

More detailed gravity data have been recently used by Delgado-Rodríguez (1995), García-Pérez (1995), Campos-Enríquez *et al.* (2000) and Ortega-Gutiérrez *et al.* (2008). These gravity measurements were made with a Worden Master Gravity Meter every 200 m along a net of closed traverses of 5 – 8 km. Maximum closure times were two hours. Measurements were tied to the Tacubaya gravity pendulum base station in Mexico City belonging to the International Gravity Standardization Net 1971 (IGSN71). The overall accuracy of the data set is 0.5 mGal. Details are given in Delgado-Rodríguez (1995) and García-Pérez (1995).

From this more detailed gravity data set, a 140 km long, gravity profile perpendicular to main gravity anomalies was obtained along the meridian 99° 30’.

The first 10 km are located in the Valley of Toluca (Lerma

Basin) (yellow line in Figure 2). The rest of the profile is in the Morelos Basin (Morelos Platform). It begins at 19° 12.5' north latitude, in a Pliocene product covered plain (southern Lerma Basin) comprising the site of a seismic sequence (Yamamoto and Mota, 1988). Continuing to the south, the profile runs parallel to southern Sierra de Las Cruces (to the west of San Miguel and La Corona volcanoes). It crosses Las Tres Cruces cinder cone complex where the Holotepec volcano is located (to the east of the Nevado de Toluca volcano). In this area it cuts the E-W Tenango Fault System (Tenango Fault, Joquicingo-San Pedro Fault, and other NW-SE faults) (Bloomfield and Valastro, 1974; García-Palomo *et al.*, 2000; Norini *et al.*, 2006) and passes 2 km to the east of Tezontle volcano (about 10 km west of Zempoala), and west of Malinalco (*i.e.,* about 20 km west of Cuernavaca). Here, the profile already traverses the Zunpahuacan horst (García-Palomo *et al.*, 2000) where Mesozoic limestones rest on the Ixtapan-Teloloapan volcano-sedimentary and metamorphic sequence. This N-S strip of Cretaceous rocks extends to Taxco and Iguala. Between Iguala and Taxco, the Morelos Formation rocks crop out and constitute the top of a topographic high – Cerro Grande. In this portion, the profile is cut by the NW-SE Tetipac and Chichila faults, the southernmost mapped structures of the Taxco-San Miguel de Allende Fault System (Alaniz-Álvarez *et al.*, 2002). The rest of the profile is covered by rocks of the Zicapa Formation. The profile ends at 18° north latitude, some kilometers before the Huizillipec sedimentary fold dome already in the Balsas River Basin (*i.e.*, Cerca-Martínez, 2004).

In the western portion of the Morelos Platform, the rocks of the Morelos Formation folded in a N-S direction are observed to thrust rocks of the Mezcala and Zicapa formations and even younger rocks. The southern profile runs some kilometers east and parallel to the Teloloapan thrust (Telf in Figure 2) (*i.e.*, Cabral-Cano *et al.*, 2000a, 2000b). The Acatlan Complex is located about 90 km to the east of the southern end of the profile.

A regional-residual separation was performed (Figure 3). The respective residual anomaly (Figure 3c) is featured, in the Toluca Valley, by a gravity low of about -20 mGal featured by a gradient with several steps, attaining a local high of about 24 mGal around the latitude of Chalma (about km 35 in the profile). Then, the gravity values tend to decrease smoothly southwards giving rise to a regional 40 km length gravity high, delimited to the south by a gradient at the latitude of Taxco volcanic center. Afterwards, the values tend to decrease faster between kilometers 70 and 80. Around Iguala, they climb again. The gravity low between Taxco and Iguala represents a conspicuous gravity feature.

The forward modeling of the gravity residual anomaly was based on Talwani *et al.* (1959). Since the profile cuts geologic structures with a general N-S strike and widths of 40 – 50 km, a 2 – 1/2 D forward modeling was done (*i.e.*, Rasmussen and Pedersen, 1979).

The gravity model was constrained by the geologic maps of the study area (*i.e.*, Rivera-Carranza *et al.*, 1998; De la Teja-Segura, 2002), as well as by available geologic studies (*i.e.*, Meschede *et al.*, 1996; Cabral-Cano, 2000b; Salinas-Prieto *et al.*, 2000; Alaniz-Álvarez *et al.*, 2002; Cerca-Martínez, 2004; Morán-Zenteno *et al.*, 2005). Topography (Figure 3d) was also included as a constraint in the modeling process.

According to the model (Figure 4), at the latitude of the Chichinautzin Range and of the Nevado de Toluca volcano, basement blocks (calcareous rocks) are downward displaced along six faults into the Lerma Basin (southern Toluca Valley) where it attains depths between 2 and 3 km.

These faults are indicated by the well defined steps and respective slopes featuring the major gradient facing the Basin of Toluca. Sediments and volcanic products of southern Lerma Basin cover existing faults. Recent seismic activity (Yamamoto and Mota, 1988; this study) supports the presence of active E-W faults at the northernmost portion of the profile. Also, aligned cinder cones at the foot of Sierra de la Cruces range constitute a geomorphologic element supporting the existence of the two northernmost E-W buried faults (Figure 2). *A posteriori*, a quite good correlation is found between the rest of these north-dipping faults and the Tenango Fault System (*i.e.*, García-Palomo *et al.*, 2000; Norini *et al.*, 2006). Ongoing magnetotelluric studies support a thickness of volcano sedimentary infill of about 2 to 3 km in this region (Campos-Enríquez *et al.*, 2013).

These north-dipping faults reproduce, fairly well, the steep gravity gradient of this area. The gravity model south of Chichinautzin Range shows shortening structures probably associated with transpressive regimes acting during the Late Cretaceous and the early Paleogene (*i.e.*, Meschede *et al.*, 1996; Cabral-Cano, 2000a, 2000b; Salinas-Prieto *et al.*, 2000; Alaniz-Álvarez *et al.*, 2002; Cerca-Martínez, 2004).

Southwards the faults dip to the south. The main gravity high between 35 and 45 km was modeled in function of a structural high (simulating the Zunpahuacan horst of García-Palomo *et al.*, 2000), where the Ixtapan-Teloloapan volcano-sedimentary and metamorphic sequence underlie Mesozoic limestones. According to the model, the basement and lower sequences are overthrusting the limestones. This structural high resembles a positive flower structure (structures normally associated with transpressive tectonics) probable acting during the Paleogene.

According to Rivera-Carranza *et al.* (1998), De la Teja-Segura *et al.* (2002) and Cerca-Martínez (2004), this cover of Cretaceous rocks extends to Taxco and Iguala, constituting a strip with a N-S direction. The wide gravity anomaly high between 40 and 70 km can be interpreted as a repetition of the Mesozoic sequences (Morelos and Mezcala Formations) simulating a N-S recumbent fold in agreement with the thrusting tectonic style as have been mapped in the Morelos Platform (*i.e.*, Rivera-Carranza *et al.*, 1998; De la Teja-Segura, 2002; Cerca-Martínez, 2004).

The gradient limiting the above mentioned regional

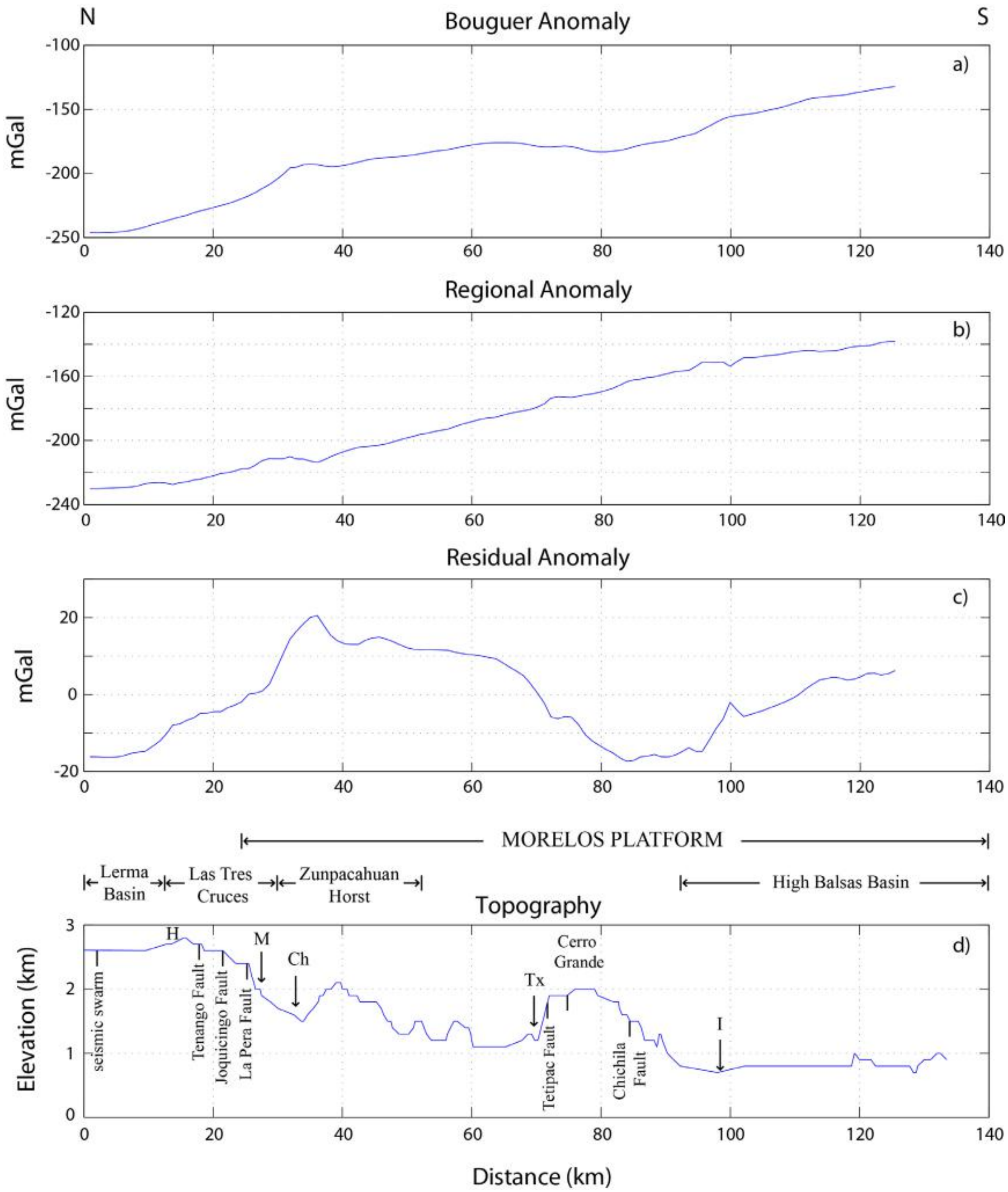

Figure 3.Gravity profile (see location in Figure 2). a): Bouguer anomaly; b): regional anomaly; c): residual anomaly; d) topographic profile. H: Holotepec volcano, M: Malinalco, Ch: Chalma, Tx: Taxco Volcanic Field, I: Iguala City.

gravity high to the south has been interpreted as a south-dipping fault (between km 70 and 75) (see Figures 2, 3, and 4) partially coinciding with the northwestern tip of Los Amates, Tuxpan, and other unnamed NW-SE lateral faults mapped to the east of the profile (Cerca-Martínez, 2004; Morán-Zenteno *et al.*, 2005). But they also can be correlated with one of the southernmost NW-SE faults of the Taxco-San Miguel de Allende Fault System: Tetipac Fault (Alaniz-Álvarez *et al.*, 2002) that cross the Taxco area and would reach the profile obliquely. The faults affecting the Taxco volcanic center had a strike-slip phase during the Paleogene. Because of it, we simulated the fault as an old inactive shear-zone affecting the greenschists of Taxco and now covered by volcanic rocks.

The gravity low between 75 and 95 km (beneath the Iguala region) was interpreted as a repetition of the sedimentary sequence simulating a recumbent syncline or the effect of thrusting. Such structures are present in the Alto Rio Balsas Basin. The southern gradient limiting this gravity low (at about km 100) was interpreted as a north dipping

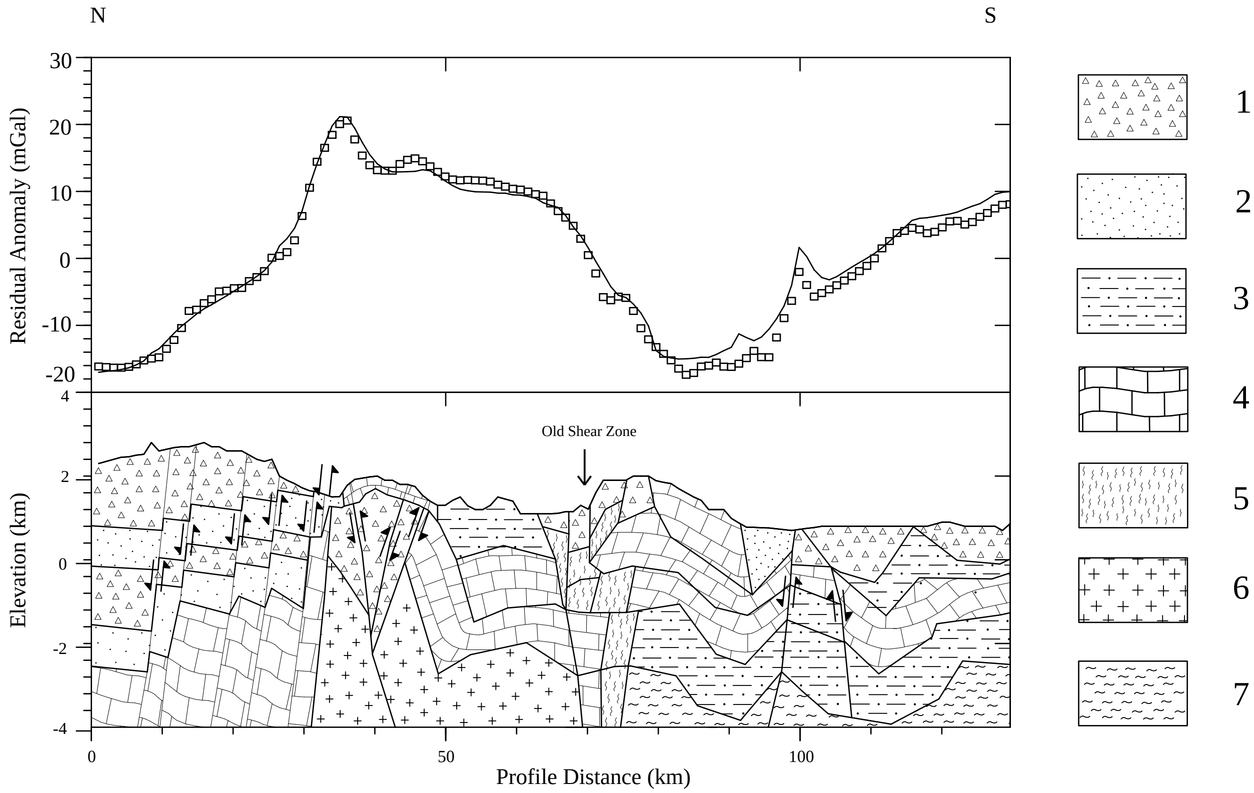

Figure 4. Gravity model (see location in Figure 2). Upper panel displays observed and calculated residual anomaly. Lower panel: model. Geologic units and respective density range are as follows. 1: undifferentiated volcanic rocks (2.63 – 2.81 gm/cm³); 2: undifferentiated infill (2.52 – 2.69 gm/cm³); 3: limestones of the Mezcala Formation (2.55 – 2.70 gm/cm³); 4: fault rock (2.52 – 2.72 gm/cm³). 5: limestones of the Morelos Formation (2.60 – 2.85 gm/cm³); 6: crystalline (igneous) basement (2.76 – 2.84 gm/cm³); 7: metamorphic basement (2.60 – 2.72 gm/cm³).

fault (corresponding to the southeastern projection of the Chichila fault described by Alaniz-Álvarez *et al*., 2002).

Our model suggest that the Tetipac-El Muerto, and Chichila faults and those mapped to the east of the profile (*i.e.*, Los Amates, Tuxpan, etc.) form a stepwise continuous NW-SE fault system that can be traced southeastwards to the Acatlan Complex.

In the rest of the profile the sedimentary sequence and underlying basement tend to be shallow. The profile ends at 18º north latitude before the sedimentary dome of Huiziltepec. In this last portion, we interpreted the presence of a recumbent syncline, and a duplication of the sedimentary formations due to underthrusting.

5. Seismicity in the southern Mexico Basin

Devastating subduction related earthquakes in Mexico have fostered seismic research on understanding their causes and effects on major cities. However, crustal seismic activity in the Mexico Basin, and in particular that originating along the Chichinautzin Range, has been less studied because of the lower magnitudes (< 4 Mc – coda magnitude), and shallow depths (< 20 km).

Nevertheless, seismic studies conducted with a limited number of seismic stations have indicated the frequent occurrence of local earthquakes in zones close to and within the Mexico Basin (*i.e.*, Figueroa, 1971; Prince, 1974; Havskov, 1982; Yamamoto and Mota, 1988), some of intensity V MM (Modified Mercalli) (Havskov, 1982). Inhabitants felt that the earthquakes of February 4 and 15, 1981 were of unusual 3.2 Mc magnitude. Recent events include that of February 2, 1984 (Rodríguez *et al.*, 1984), and of 21 January, 1995 (UNAM and CENAPRED Seismology Group, 1995). Lermo *et al.* (1995) and Delgadillo (2001) have again indicated the constant occurrence of low magnitude earthquakes.

Based on events from the recorded initial seismic activity and that documented since 1970, we characterize 70 earthquakes registered in the neighboring area and in the Mexico Basin; source parameters are obtained and correlated with the documented faults. In particular, we analyze 4 main seismic zones: I), Xochimilco-Milpa Alta, II) Xochitepec, III) Zempoala, and IV) Toluca.

6. Data

Analyzed seismic events come from a compilation based on the studies of Bravo *et al.* (1988), Lermo *et al.*

(1997), Delgadillo (2001), and Pacheco *et al.* (2003). It also includes analog and digital records from the different seismic networks gradually installed since 1970: Servicio Sismológico Nacional (SNN), Red Sismotelemétrica del Valle de México from the Engineering Institute (SISMEX), Red Sísmica del Valle de México (RSVM), and the Popocatepetl volcano monitoring net from the Centro Nacional de Prevención de Desastres (CENAPRED). Figure 5 shows the location of the seismic stations of these networks.

A total of 70 earthquakes were compiled and relocated using SEISAN (8.1 version) (Havskov and Ottemöller, 2005), considering a 1.73 Vp/Vs ratio and the Mc coda magnitude). We used the magnitude of Hasvkov and Macías (1983), and the velocity model of Lermo *et al.* (2001) (Table 2). Correspondingly, depths were less than 20 km and magnitudes range between 1.1 and 4.0 Mc (Figure 5, Table 3). Hypocentral location errors are less than 5 km for zones I and II, but larger than 5 km for zones III and IV due to a poor azimuthal coverage in these two last zones.

Table 2. Velocity model of Lermo *et al.* (2001).

Vp (km/s)	Dep th. (km)
2.9	0
5.2	1
5.8	3
6.6	15
8.1	45

7. Seismicity

7.1. Zone I: Xochimilco-Milpa Alta

For this zone, 25 local earthquakes, with magnitudes between 2.2 and 4.0 Mc, were relocated. The spatial distribution (Figure 6I) presents an approximately E-W trend, and correlates with the Xochimilco Fault. According to the NE-SW profile A-A´ (Figure 6II) events are located at shallow depths (7 – 15 km), and distributed around a vertical plane. Recent seismicity migrates southwards close to cone lineament number 12 as proposed by Márquez *et al.* (1999b). This is the most seismically active zone of the Mexico Basin according to Figueroa (1971), Prince (1974) and Bravo *et al.* (1988). The larger magnitude corresponds to an event recorded on 21 January, 1995 (UNAM and CENAPRED Seismology Group 1995).

7.2. Zone II: Xochitepec

A total of 28 earthquakes, with magnitudes between 1.1 and 3.7 Mc, were relocated. The largest ones are that of February 7, 1984 (Rodríguez *et al.*, 1984) and of November 6, 2003 (Velasco, 2003). The respective spatial distributions show a general NW-SE orientation (Figure 7I). However, seismicity of the second event, presents an approximately NWW-SEE cluster. This seismicity is distributed between lineament number 10 of Márquez *et al.* (1999b) (also with the eastward continuation of the Azteca Fault–number 14 in the figure), and cone lineament 11 of Márquez *et al.* (1999b) and fault 7 inferred by Vázquez-Sánchez and Jaimes-Palomera (1989). The hypocenters (Figure 7II) occur at depths between 5 and 18 km, around a vertical plane. Shallow seismicity corresponds to the second event. Márquez *et al.* (1999b) also found secondary cone lineaments with a NW-SE orientation (one such NW-SE cone lineament can be observed in Figure 7I). This orientation might be related to subordinated faults (*i.e.*, Riedel type faulting) associated with the main E-W faults.

7.3. Zone III: Zempoala

For this zone, 8 earthquakes were relocated, with corresponding magnitudes between 2.1 and 3.2 Mc (Figure 8I). The representative events are those of October 26, 1998 (Chavacán, 2003), that of March 1st, 2001, and April 12, 2003 (Pacheco *et al.*, 2003). All these events have well defined p and s first arrivals and are of high frequency content (*i.e.*, they are of tectonic origin). So far no tremors, etc. have been detected within the array deployed here. Their spatial distribution follows an E-W trend correlating with cone lineament number 9 of Márquez *et al.* (1999b) and the northernmost fault of Ávila-Bravo (1998), and has a general south-dip in agreement with Ávila-Bravo (1998). Depth distribution (Figure 8II) shows that hypocenters occur between 2 and 15 km.

7.4. Zone IV: Toluca

In August, 1980, a local earthquake swarm occurred in the valley of Toluca. The epicenter relocation of these 9 events, with magnitudes between 2.7 and 3.7 Mc, follows an E-W orientation (Figure 9I) similar to that observed in zone III. Even if relocation errors are larger due to less azimuthal coverage, the events are correlated with the reactivation of the Tenango Fault (Vázquez-Sánchez and Jaimes-Palomera, 1989; García-Palomo *et al.*, 2000; Norini *et al.*, 2006; García-Palomo *et al.*, 2008) (*i.e.*, a left-lateral, subvertical fault dipping to the north). The depth profile indicates a sub-vertical depth distribution between 3 and 21 km, relatively deeper that in the previous zones (Figure 9I).

8. Focal mechanisms and modeling

To characterize the source parameters, composite

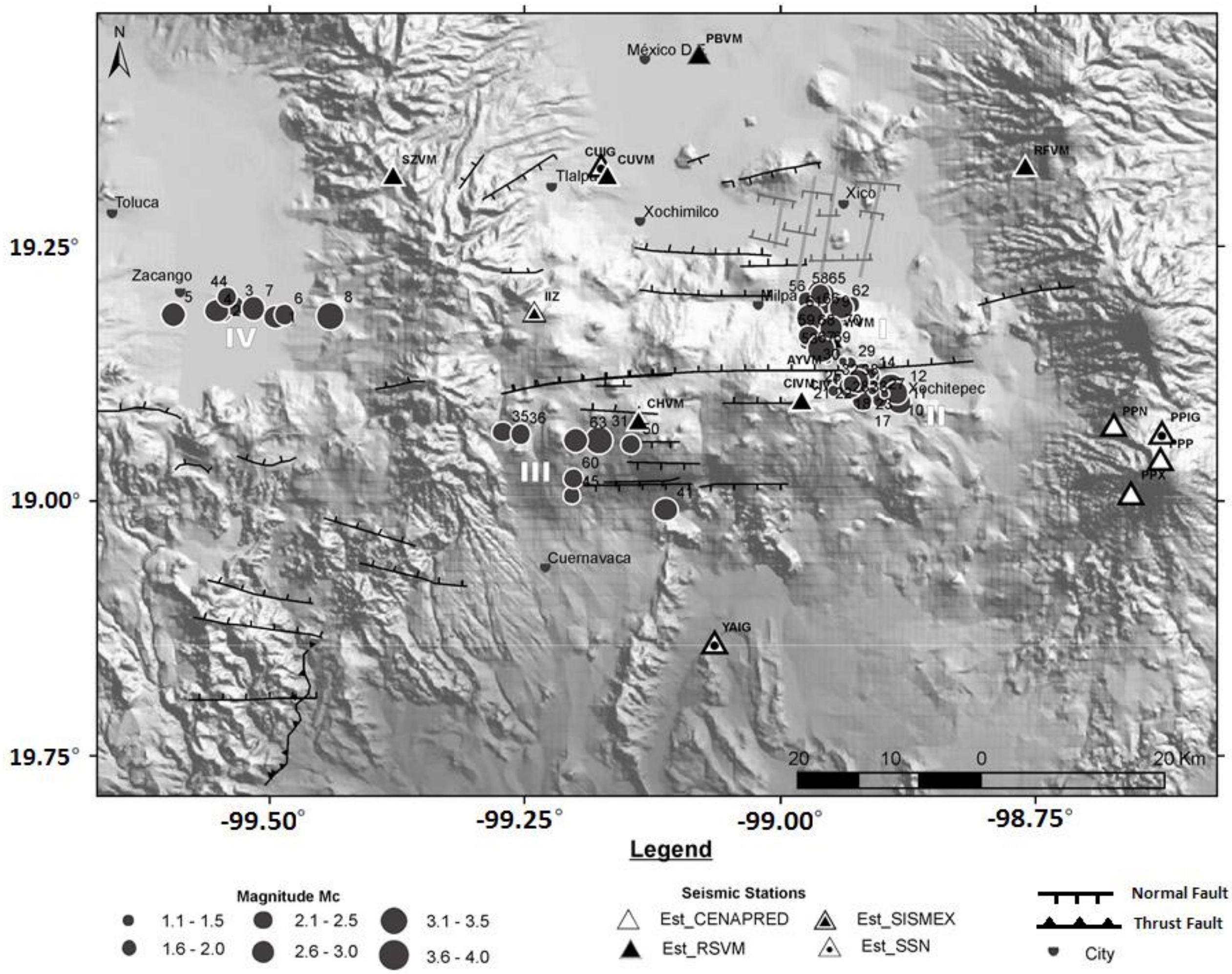

Figure 5. Relief map indicating location of the seismic stations in the Mexico Basin installed since 1970, and distribution of faults drawn with light lines (names are given in Table 1, Figures 2 and 12). Bold symbols represent the location of seismic stations indicating the name of the respective seismic network. SSN: Servicio Sismológico Nacional, CENAPRED: Centro Nacional de Prevención de Desastres. RSVM: Red Sísmica del Valle de México, SISMEX: Red Sismotelemétrica del Valle de México from the Instituto de Ingeniería of the Universidad Nacional Autónoma de México. The light gray lines represent the gravity profiles studied by Campos-Enríquez *et al.* (1997) and the respective inferred faults are shown also in light gray.

focal mechanisms were obtained. For zone III, it was only possible to obtain a simple mechanism (Figure 10 and Table 3).

The nodal plane, dipping to north (and corresponding to a normal fault) obtained for zone I (Figure 10a), would correlate with the normal Xochimilco Fault. Concerning the NW-SE right-lateral transcurrent mechanism of Figure 10b, no fault has been mapped. However, Márquez *et al.* (1999b) also reported secondary cone alignments in a NW-SE direction, and possibly this is the case. In zone III the chosen plane (Figure 10c) correlates fairly well with faults described by Ávila-Bravo (1998). The transcurrent mechanism of Zone IV correlates very well with an E-W, north dipping fault associated with the Tenango Fault system (Figure 10d). Zone II and III focal mechanisms are not very well constrained. If, for zone II, the almost north-south plane is well constrained, the other plane is weakly constrained and open to other interpretations. The mechanism for zone III is not very well constrained because its azimuthal coverage corresponds mainly to stations to the north.

In these cases we used the event epicenter distribution, as well as available geological information (faults and cone lineaments) to choose between both nodal planes. To assess the feasibility of the chosen mechanism we modeled waveforms following Bouchon (1979) corresponding to the chosen fault planes.

For this modeling, we selected events analyzed in this study, as well as from the UNAM and CENAPRED Seismology Group (1995), if they were recorded by the broadband stations CUIG, PPIG, and YAIG. Results are satisfactory (*i.e.*, shape and magnitude of first and second arrivals are similar in the observed and synthetic seismograms), as can be observed in two examples shown in Figure 11. They correspond to events of July 25, 1999

Table 3. Hypocentral parameters of 7 for the 70 analyzed seismic events. Mc, coda magnitude; Mw; magnitude moment; Mo*E+12, seismic moment in Nm; St*E+5, strength drop in Pa; Fo, corner frequency in Hz, and R, rupture radii in km.

N°	Zone	Date dd/mm/yyyy	Time hh:mm:ss	Latitude (°W)	Longitude (°N)	Depth (km)	rms	Mc	Mw	Mo*E+12	St*E+5	Fo	R
1	IV	19/08/1980	09:34:26	19.181	-99.494	3	0.4	3.2					
2	IV	19/08/1980	10:52:20	19.185	-99.547	11.3	0.5	2.9					
3	IV	19/08/1980	45:50.6	19.192	-99.535	13.4	0.6	2.7					
4	IV	19/08/1980	15:41:58	19.187	-99.552	9.7	0.8	3.1					
5	IV	19/08/1980	16:59:44	19.183	-99.595	5.6	0.9	3.4					
6	IV	20/08/1980	25:05.7	19.183	-99.486	20.7	0.3	2.7					
7	IV	23/08/1980	22:00:18	19.189	-99.516	15.3	0.9	3.1					
8	IV	27/08/1980	03:12:08	19.182	-99.441	19	1	3.7					
9	II	22/03/1983	03:29:40	19.18	-98.95	17.9	0.4	2.8					
10	II	07/02/1984	08:05:00	19.111	-98.891	9.2	0.2	3.7					
11	II	07/02/1984	08:49:46	19.097	-98.883	10.7	0.2	3.1					
12	II	07/02/1984	14:02:03	19.106	-98.886	10.2	0.3	3.1					
13	II	14/02/1984	22:57:15	19.128	-98.916	6	0.1	1.4					
14	II	15/02/1984	00:39:34	19.123	-98.911	7.9	0	2.5					
15	II	15/02/1984	08:22:39	19.112	-98.914	7.2	0.1	2.6					
16	II	15/02/1984	10:30:02	19.109	-98.948	9.8	0.1	1.7					
17	II	15/02/1984	11:17:05	19.099	-98.919	15.3	0.1	2.6					
18	II	15/02/1984	12:29:03	19.1	-98.902	17.4	0	2.1					
19	II	15/02/1984	20:21:09	19.127	-98.92	9.7	0.1	2.5					
20	II	16/02/1984	07:18:30	19.112	-98.936	8	0.1	1.3					
21	II	16/02/1984	08:47:24	19.12	-98.943	9.8	0.1	1.7					
22	II	17/02/1984	07:20:26	19.122	-98.932	6.2	0.2	1.4					
23	II	17/02/1984	08:30:44	19.108	-98.91	9.2	0.1	1.3					
24	II	17/02/1984	11:39:00	19.125	-98.912	8.1	0.2	1.7					
25	II	19/02/1984	01:16:48	19.139	-98.953	6.2	0.1	1.3					
26	II	20/02/1984	06:17:45	19.133	-98.934	7.3	0.1	1.3					
27	II	20/02/1984	07:52:26	19.105	-98.898	8.9	0.1	1.1					
28	II	20/02/1984	15:07:41	19.118	-98.937	11.6	0.1	1.7					
29	II	21/02/1984	09:24:59	19.136	-98.931	8.5	0.2	1.7					
30	II	21/02/1984	10:15:35	19.138	-98.938	7.5	0	1.1					
31	III	19/10/1985	08:28:36	19.06	-99.178	8.5	0.3	3.9					
32	II	29/07/1993	10:50:46	19.112	-98.931	14.3	0.2	3.4					
33	II	30/07/1993	08:15:42	19.118	-98.924	12.6	0.2	3.2					
34	**I**	**21/01/1995**	**05:51:52**	**19.191**	**-98.95**	**14**	**0.3**	**3.9**	**3.4**	**176**	**28**	**3.76**	**300**
35	III	12/04/1995	08:58:14	19.068	-99.272	11.3	0.1	3					
36	III	13/04/1995	17:22:03	19.066	-99.255	14.8	0.5	2.9					
37	I	06/10/1995	21:07:54	19.196	-98.943	11.5	0.1	2.5					
38	II	01/01/1996	03:23:34	19.116	-98.93	13.9	0.1	2.4					
39	I	01/01/1996	18:49:03	19.193	-98.93	12.9	0.2	2.3					
40	I	01/01/1996	19:41:21	19.196	-98.943	10.6	0.2	2.3					
41	III	14/02/1996	14:58:29	18.992	-99.112	2.2	0.4	3.2					
42	I	17/04/1996	13:19:10	19.198	-98.946	11.4	0.3	3					
43	I	07/06/1996	08:10:54	19.195	-98.941	8.7	0.4	2.7					
44	**IV**	**30/05/1996**	**11:20:48**	**19.201**	**-99.542**	**19.4**	**0.4**	**2.6**	**2.7**				
45	**III**	**20/04/1997**	**20:11:11**	**19.006**	**-99.204**	**5.8**	**0.4**	**2.1**	**2.6**	**10.1**	**1**	**2.93**	**330**
46	I	08/05/1997	22:51:03	19.193	-98.944	10.5	0.2	2.2					
47	I	26/08/1997	09:12:02	19.197	-98.949	11.7	0.3	2.5					
48	I	18/08/1998	16:27:33	19.191	-98.937	10.7	0.2	2.5					
49	I	18/08/1998	18:52:49	19.192	-98.94	14.4	0.3	2.6					
50	**III**	**26/10/1998**	**07:50:06**	**19.056**	**-99.146**	**12.4**	**0.3**	**2.9**	**2.6**	**8.9**	**5**	**5.61**	**200**
51	I	19/05/1999	20:23:05	19.195	-98.944	13.7	0.3	2.6					
52	I	22/05/1999	06:56:26	19.199	-98.953	8.5	0.3	2.7					
53	**I**	**07/06/1999**	**00:24:14**	**19.182**	**-98.96**	**13.6**	**0.4**	**2.9**	**2.5**	**5.9**	**0.9**	**2.64**	**300**
54	**I**	**25/07/1999**	**14:26:01**	**19.194**	**-98.957**	**7.9**	**0.4**	**3.3**	**2.6**	**9.6**	**1**	**2.9**	**370**

Table 3 (Continuation). Hypocentral parameters of 7 for the 70 analyzed seismic events. Mc, coda magnitude; Mw; magnitude moment; Mo*E+12, seismic moment in Nm; St*E+5, strength drop in Pa; Fo, corner frequency in Hz, and R, rupture radii in km.

N°	Zone	Date dd/mm/yyyy	Time hh:mm:ss	Latitude (°W)	Longitude (°N)	Depth (km)	rms	Mc	Mw	Mo*E+12	St*E+5	Fo	R
55	**I**	**07/12/1999**	**13:53:49**	**19.205**	**-98.961**	**11.7**	**0.2**	**3.3**	**3.6**	**297.4**	**24**	**2.91**	**280**
56	I	10/04/2000	07:53:23	19.198	-98.974	12.7	0.5	2.5					
57	I	11/06/2000	01:29:27	19.196	-98.959	11.6	0.3	2.5					
58	I	06/07/2000	08:36:25	19.204	-98.956	10.8	0.3	2.7					
59	I	06/07/2000	13:15:34	19.193	-98.957	14	0.4	3					
60	III	01/03/2001	16:26:45	19.022	-99.203	2.3	0.4	2.9					
61	I	08/01/2003	21:27:22	19.18	-98.97	13	0.3	3					
62	I	16/01/2003	08:21:15	19.19	-98.94	15	0.3	3.1					
63	III	12/04/2003	14:28:21	19.06	-99.2	9	0.3	3.1					
64	I	11/11/2003	04:53:40	19.173	98.956	7.4	0.3	2.6					
65	I	11/11/2003	08:43:54	19.203	-98.961	5.2	0.3	2.8					
66	I	16/11/2003	03:17:13	19.18	-98.97	7	0.3	4					
67	II	16/11/2003	05:09:20	19.157	-98.972	7.8	0.3	2.3					
68	II	26/11/2003	05:04:24	19.163	-98.972	9.7	0.3	2.8					
69	II	12/03/2006	01:41:32	19.15	-98.96	5	0.3	3.7					
70	I	12/03/2006	01:47:21	19.17	-98.95	5	0.3	3.5					

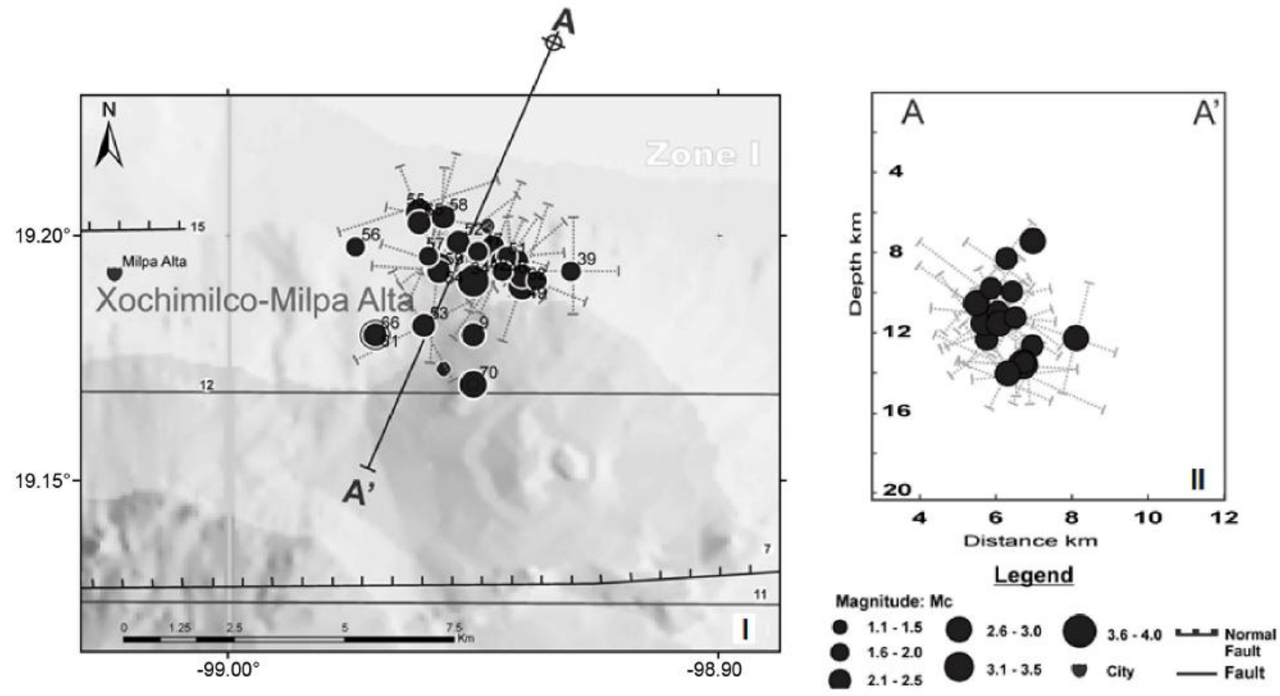

Figure 6. Earthquake localization in Zone I (Xochimilco-Milpa Alta) with corresponding error bars. I) plan view, II) profile A-A'. Number tags of faults and lineaments are the same as in Figure 2 and Table 1. Seismic events indicated by black filled circles. Numbers close to seismic events indicate the event number in Table 3.

of zone I (Xochimilco-Milpa Alta), and that of October 26, 1998 of zone III (Zempoala). Furthermore, following Brune (1970), the source parameters were estimated: seismic moment (Mo), stress drop (St), corner frequency (Fo), and source radius (R) (Table 4).

9. Discussion

The gravity model obtained in this study enables us to infer that the faults discussed in this study are correlated, and constitute a fault system (the Aztlán Fault system). Next, we will indicate how these faults, which were already mapped and reported by geologic and geophysical studies

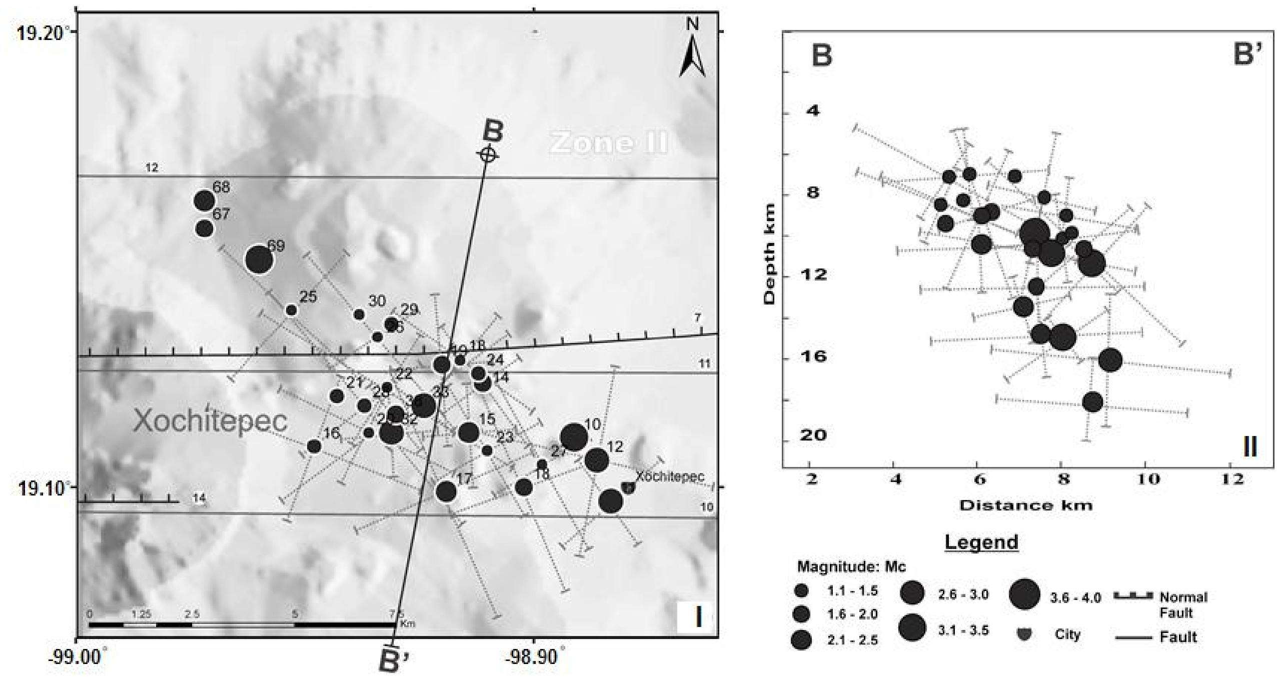

Figure 7. Earthquake localization in zone II (Xochitepec) with their corresponding error bars. I) plan view, II) profile B-B´. Number tags of faults and lineaments are the same as in Figure 2 and Table 1. Seismic events indicated by black filled circles. Numbers close to seismic events indicate the event number in Table 3.

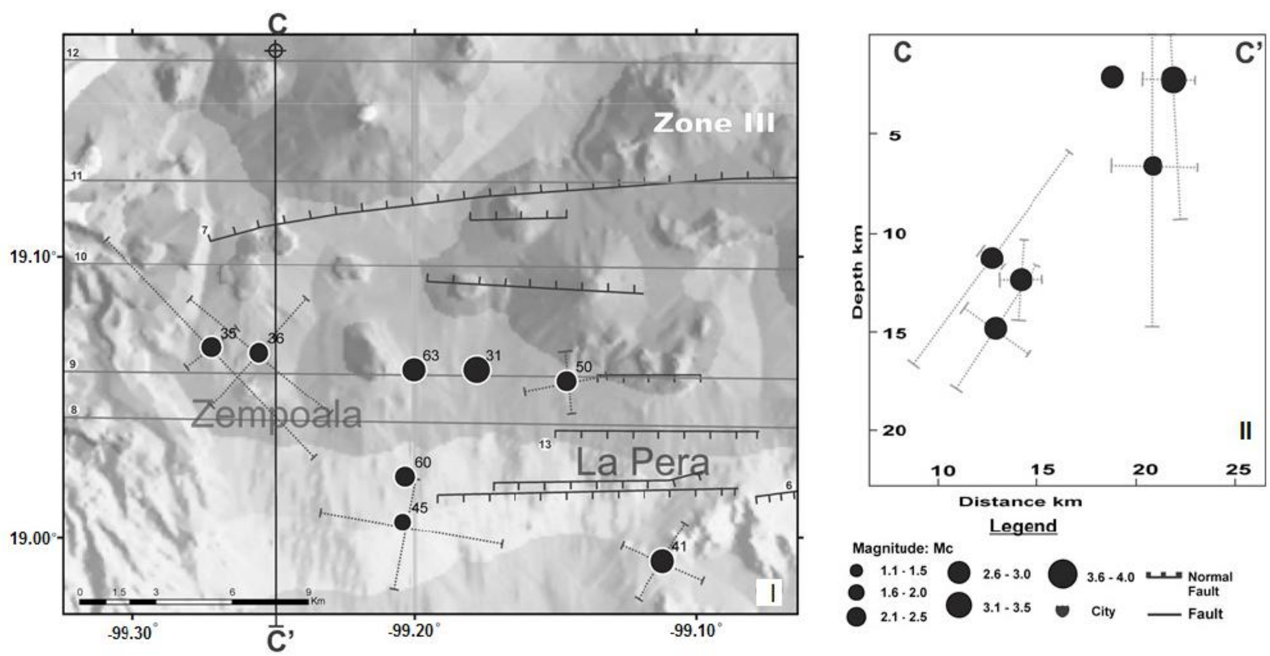

Figure 8. Earthquake localization in Zone III (Zempoala) with their corresponding error bars. I) plan view, II) profile C-C´. Number tags of faults and lineaments are the same as in Figure 2 and Table 1. Seismic events indicated by black filled circles. Numbers close to seismic events indicate the event number in Table 3.

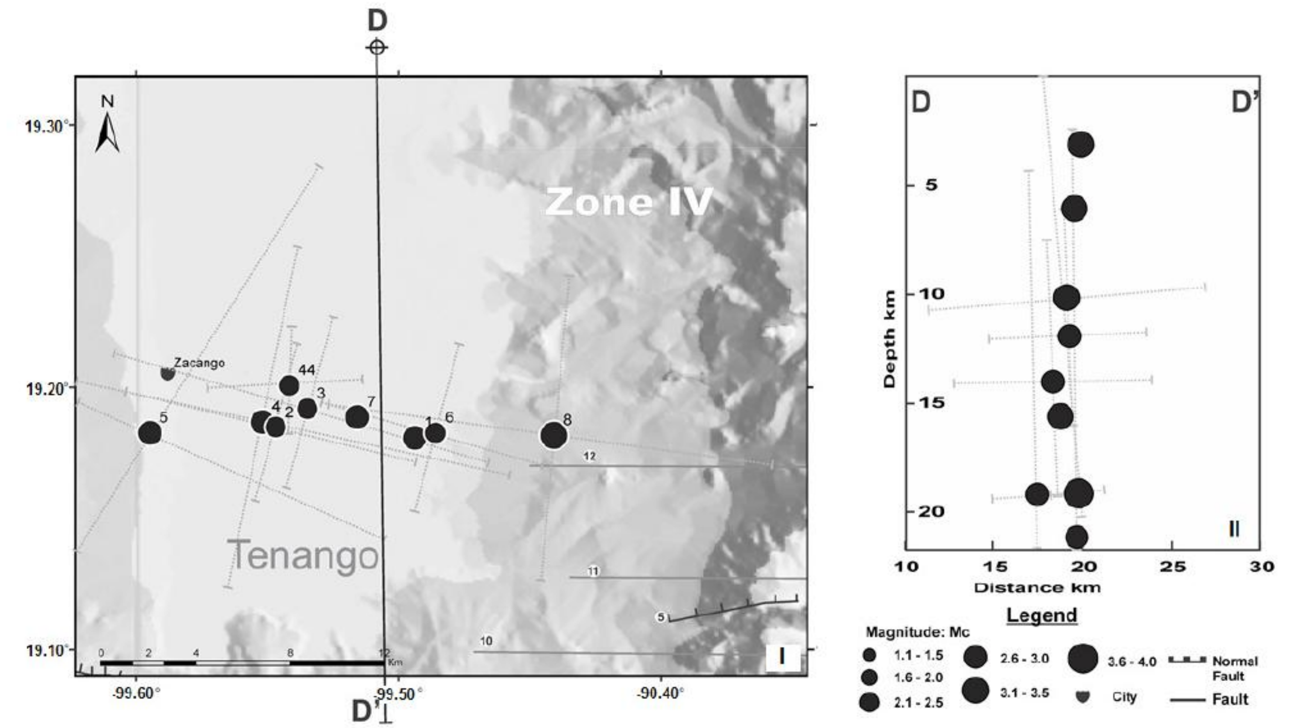

Figure 9. Earthquake localization in Zone IV (Toluca) with corresponding error bars. I) plan view, II) profile D-D´. Number tags of faults and lineaments are the same as in Figure 2 and Table 1. Seismic events indicated by black filled circles. Numbers close to seismic events indicate the event number in Table 3.

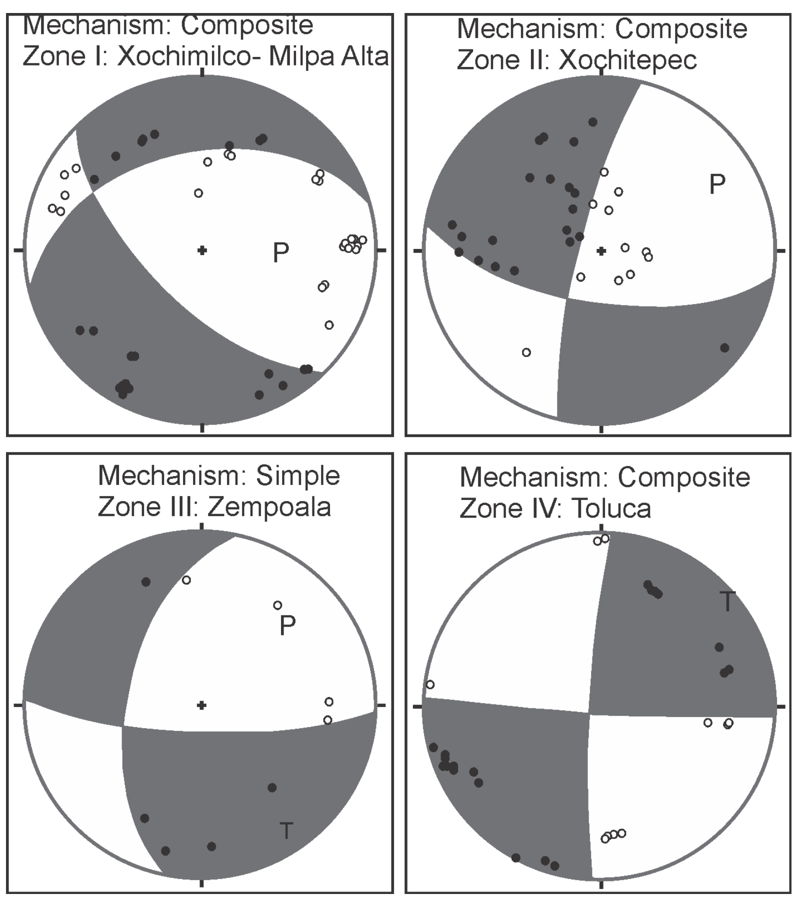

Figure 10. Focal mechanism representative of each of the four studied zones.

Table 4. Fault parameters obtained from the focal mechanisms. Shaded areas represent the principal fault planes. T and P, compression and tension axis.

Zone	Focal Mechanism	Plane	Strike (Φ, °)	Dip (δ, °)	Rake (λ, °)
I	Composite	A	135.2	65	-55.1
	Normal-fault	**B**	**256.1**	**42**	**140.8**
II	Composite	**A**	**99**	**65**	**-10.8**
	Right-lateral	B	193.6	80.2	-154.6
III	Simple	**A**	**92**	**77**	**-36.6**
	Right-lateral	B	191.5	54.4	-163.9
IV	Composite	**A**	**93**	**87**	**174.3**
	Left-lateral	B	183.3	84.3	3

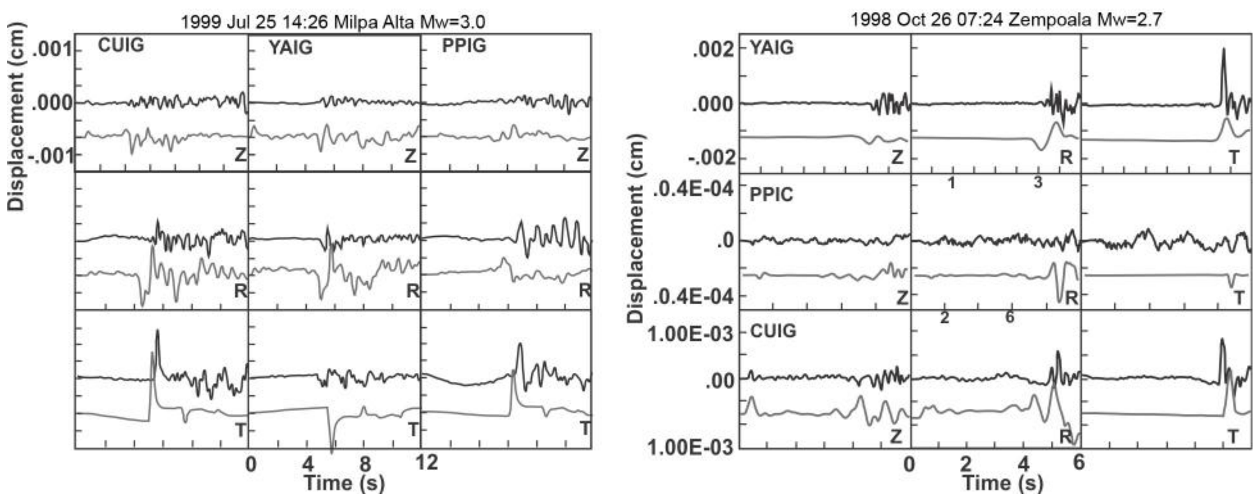

Figure 11. Waveform modeling of earthquakes recorded on July 25, 1999, and October 26, 1989, in stations CUIG, YAIG, and PPIG from SSN seismic networks.

respectively, correlate with the gravity model. We will proceed from west to east (and from north to south in the model).

1. According to the gravity model, the Tenango Fault System comprises a series of north dipping faults, some of them covered by volcanic and sedimentary products. At depth, the northernmost model fault in our model correlates quite well with the area where a seismic sequence has been reported by Yamamoto and Mota (1988). This fault can also be correlated with the northern alignment of Márquez *et al.* (1999b) (number 12 in Figure 2). This alignment is featured by seismic activity at its western and eastern ends (Lerma Basin and Xochitepec areas).
2. The central alignment of Márquez *et al*. (1999b) (number 10 in Figure 2), when extrapolated to the west, coincides fairly well with the Tenango Fault (number 1 in Figure 2). It correlates quite well with a north-dipping fault (number 5 in Figure 2) mapped by García-Palomo *et al.* (2008) to the west of the southern Sierra de Las Cruces (around La Corona Volcano). The westward extrapolation of this central lineament correlates with the second model fault. The western tip of the fault trace reported by Vázquez-Sánchez and Jaimes-Palomera (1989) (number 7 in Figure 2) joins this central alignment. The major fault inferred by Campos-Enríquez *et al.* (2000) to limit the Mexico Basin (number 14 in Figure 2) coincides with this central alignment when extrapolated to the surface. We

propose that this central major crustal fault be named Aztec Fault.

3. The two northernmost faults mapped by Ávila-Bravo (1998) (*i.e.*, La Pera Fault system) (number 13 in figure 2) coincides with the southern lineaments (number 8 and 9 in Figure 2) of Márquez *et al.* (1999b). Seismic activity is reported along this lineament around Zempoala (this study). The third model fault also coincides with this lineament.
4. The Tenango Fault System southern faults (San Pedro and Joquicingo) coincide in latitude with the second northernmost fault of Ávila-Bravo (1998) (number 13 in Figure 2), as well as with La Pera Fault as defined by García-Palomo *et al.* (2008) (number 6 in Figure 2). However, the respective vergences are opposite. San Pedro and Joquicingo faults coincide with the third model fault.
5. The Xochimilco Fault (number 15 in Figure 2; García-Palomo *et al.*, 2008) can be extrapolated to the west up to the north-dipping fault mapped by these authors to the north of Ajusco Volcano (number 4 in Figure 2).
6. The Xicomulco Fault (number 16 in Figure 2; García-Palomo *et al.*, 2008) correlates quite well with the faults delimiting graben and half-graben type structures in the Chalco sub-basin (number 17 in Figure 2; Campos-Enríquez *et al.*, 1997). It is featured by seismic activity around Milpa Alta (Rodríguez *et al.*, 1984; UNAM and CENAPRED Seismology Group, 1995, this study).

The location of the first modeled south-dipping fault (about km 35 in the gravity model of Figure 2) coincides with the southern limit of the Chichinautzin Range. South of this fault, the Mesozoic rocks are relatively shallow compared to their position in the Lerma Basin (correlating with the subsoil geology of the Mexico Basin). According to the gravity model, the south-dipping La Pera Fault postulated by Delgado Granados *et al.* (1997) and Delgado-Granados *et al.* (1999) corresponds to a relative shallow fault. Contrastingly, the north-dipping fault proposed by Campos-Enríquez *et al.* (2000), also corroborated in the Lerma Basin, is more conspicuous (*i.e.*, deeper).

Figure 12 indicates that the 70 analyzed events distribute themselves along and around several of the faults already mentioned here. Similar results were obtained by Figueroa (1971), Prince (1974), Rodríguez *et al.* (1984), Yamamoto and Mota (1988), Lermo *et al.* (1995), the UNAM and CENAPRED Seismology Group (1995), and Delgadillo (2001). Results from the simple and composite focal mechanisms are in agreement with the orientation and dip of the Xochimilco, Tenango, and La Pera faults. The transcurrent mechanism for Zone II and south-dip would indicate that the tectonics is complex (*i.e.*, piecewise changes: en echelon tectonics, Riedel-type faulting).

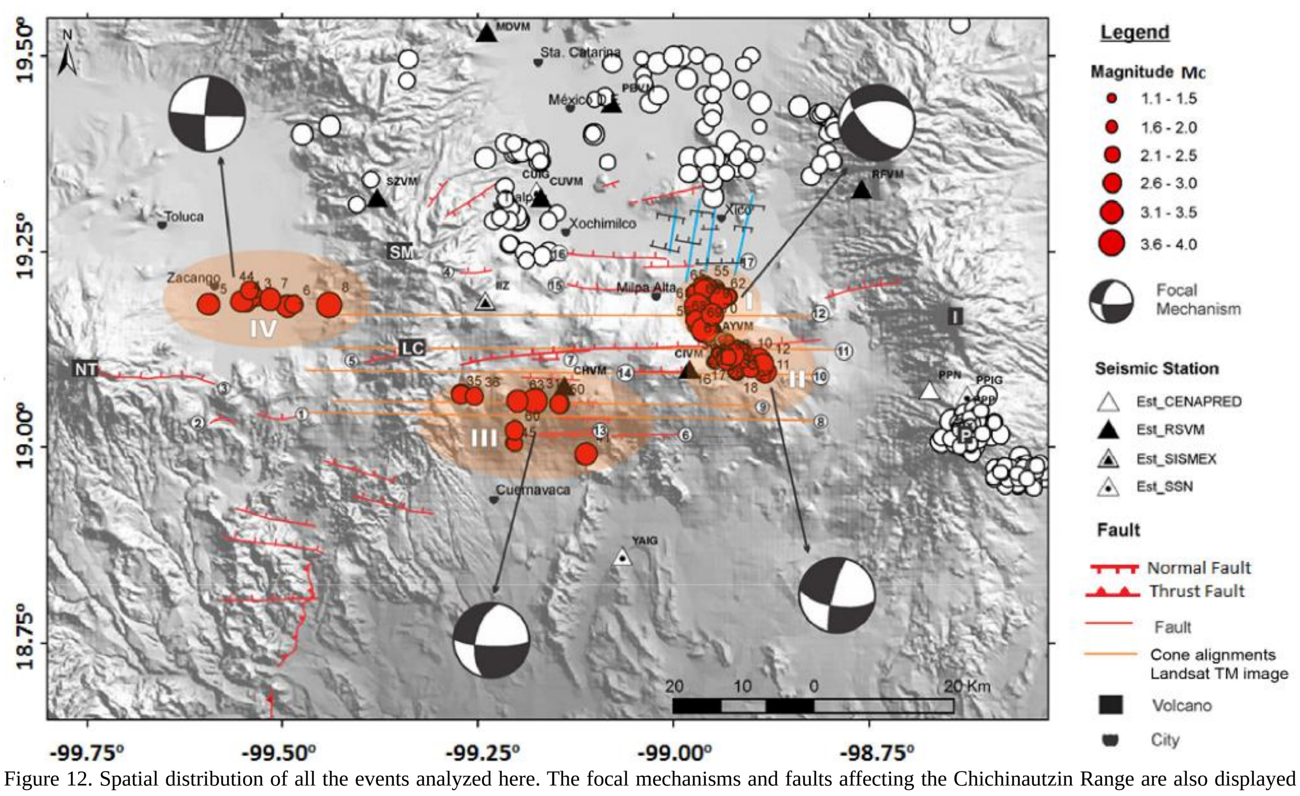

Figure 12. Spatial distribution of all the events analyzed here. The focal mechanisms and faults affecting the Chichinautzin Range are also displayed for the four zones considered. Numbers inside circles signify faults and lineaments (see Figure 2 and Table 1). Other numbers refer to events (see Table 2). Orange lines represent cone lineaments of Márquez *et al.* (1999). Lines in blue represent gravity profiles studied by Campos-Enríquez *et al.* (1997).

Finally, it is interesting to note that in the valley of Puebla-Tlaxcala, E-W faults delimit the Tlaxcala graben (Lermo-Samaniego *et al.*, 2006; Lermo-Samaniego and Bernal-Esquia, 2006). The respective southern master fault correlates in position with the above mentioned E-W faults. If this correlation can be documented in a future study, it would imply that this fault system is 100 km longer than the value here reported.

The origin of the Chichinautzin Range is related to the evolution of the Mexico Basin and this, as a consequence, also has a close relationship with the TMVB tectonics. Several models have been proposed for the nature and origin of the TMVB. For several years there has been a general agreement that it is related to oblique convergence of the Cocos plate. Its oblique location with respect to the Middle America Trench is accounted for by the change in subduction dip along southern Mexico. Other proposals include, for example, that it represents an ancient suture (Mooser, 1969; Le Pichon and Fox, 1971), a zone of strike-slip displacement (Gastil and Jensky, 1973), and Shurbet and Cebull (1984) have proposed that it represents the limit of an incipient micro-plate.

However, in the last decade, a large number of studies have contributed to a better understanding of the TMVB features. These studies have indicated, in particular, a large variety of rocks and volcanic styles. Several geophysical, geological and geochemical aspects cannot be accounted for by the subduction model.

In this way the origin of the TMVB is a subject of debate. To account for the existence of mafic rocks, Márquez *et al.* (1999a) proposes, in particular for the origin of the Chichinautzin Range, a mantle plume (*i.e.*, OIB-type magmatism). Extensional tectonics related to rift processes has been advanced by Sheth *et al.* (2000), Verma (2000), Verma (2002), Sheth *et al.* (2002), and Velasco-Tapia and Verma (2013). Ferrari (2004) proposed the eastward displacement of a tear in the subducting plate in combination with a pre-existing weakness zone (*i.e.*, related to the above mentioned models).

The central TMVB is being deformed by seismically active E-W normal faults (Suter *et al.*, 1992). Minor left-lateral displacement is associated with this intra-arc extension (Suter *et al.*, 2001a, 2001b). According to Suter *et al.* (1992), the observed tension stress can be associated with isostatic compensation processes of the highlands of central Mexico. On the other hand, the left-lateral component can also be explained by means of the compressional far-field stress due to the convergence of the North America and Cocos plates at the MAT. Thus the normal fracturing and its left-lateral component might be accommodating trench parallel movement of tectonic blocks in southern Mexico. This stress state would give rise to the proposed rifting processes (*i.e.*, Sheth *et al.*, 2000; Verma, 2000; Verma, 2002; Velasco-Tapia and Verma, 2013). Indeed, recently Ego and Ansan (2002) proposed that the slip partitioning taking place at the convergence zone is accommodated by the normal E-W oriented faults with left-lateral component of the central TMVB. Meschede *et al.* (1996) had already proposed stress transmission across southern Mexico as a mechanism to explain correlation of convergence direction and stress states in southern Mexico since the Cretaceous.

Thus, this study documents the existence on the southern limit of central TMVB of an active fault system. In this way, it turns out that the Toluca and Mexico basins are bounded to the north and to south by active E-W normal faults. This implies that there is an extensional tectonic regime associated with the origin of these depressions. In other words we have a rifting process such as has been invoked by Sheth *et al.* (2000), Verma (2002), and Velasco-Tapia and Verma (2013).

10. Conclusions

In particular, the gravity model enables integration into the major Aztlán Fault System the different faults mapped up to today that affect the Chichinautzin Range. According to the gravity model, the Chichinautzin Range was constructed on top of Mesozoic calcareous rocks lying above a metamorphic basement. To the north and south this basement is downfaulted. Nevertheless the north dipping faults displace the basement downward to greater depths (2 to 3 km) in the Toluca and Mexico basins. As block faulting proceeded, the edge of the basement migrated southwards. Magma used segments of these faults as conduits to the surface. In the Morelos basin, the correlating rocks are at shallower depths. This system is a major tectonic feature of at least 100 km in length and 30 – 40 km in width, a density of approximately one E-W fault each three kilometers, and a local extension of about 10 %. Probably it extends a great distance eastwards.

A very important result derives from the seismic study: the active nature of this fault system. Also, seismic studies indicate that the fault system reaches the brittle-ductile transition crustal zone (about 15 km), but given its length, it should reach lower crustal levels (about 40 km).

Orientation and dips obtained from simple, composite mechanism (and confirmed by waveform modeling) corroborate fairly well the faults mapped so far (the northern Xicomulco Fault, the central major Aztec Fault, and southern La Pera Fault).

This E-W fault system would have fractured the crust intensely beneath the Sierra de Chichinautzin, in conjunction with the Basin and Range NW-SE fault system, as well as the associated NE-SW thrust and fault system of the Sierra Madre Oriental. This high degree of fracturing has enabled the relatively fast emplacement of large quantities of volcanic material to give rise to the Chichinautzin Range, closing the Mexico Basin to the south.

This study indicates that not only the northern portion of central TMVB is under extension (*i.e.*, Suter *et al.*, 2001a, 2001b) but also its southern portion, in particular, the southern Toluca and Mexico basins, thus indicating extensional tectonics for the origin of these basins. The gravity modeling indicates that faults of the Taxco-San Miguel de Allende system affect the basement of the Morelos basin much further south.

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