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Volcanic stratigraphy and geological evolution of the Apan region, east-central sector of the Trans-Mexican Volcanic Belt

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RESUMEN

La región de Apan está situada entre los sectores este y central del Cinturón Volcánico Transmexicano (CVTM), su registro geológico muestra una interacción intermitente entre volcanismo y tectónica. Las rocas más antiguas en el área fueron emplazadas hace 13.5 Ma, seguidas por un hiatus volcánico de casi 10 Ma. El volcanismo en el área ocurrió entre ~3.0 y 1.5 Ma; con la actividad más reciente durante el Pleistoceno Tardío (~42-31ka). Las rocas volcánicas de la región de Apan varían en composición de basalto a riolita (50-75 wt.% SiO_2) y muestran afinidad calco-alcalina; sus características geoquímicas indican que son productos eruptivos procedentes de una zona de subducción. Estudios geológicos y estratigráficos detallados utilizando un mapa con base digital escala 1:100 000 para la compilación de datos previos y nuevos, combinados con fechamientos K- Ar, demuestran que la distribución de los centros volcánicos en la región de Apan está controlada en gran medida por un sistema de fallas normales NE-SW y estructuras de fosas y pilares asociadas, como resultado de un campo de esfuerzos con el esfuerzo mínimo principal (σ3) orientado hacia el NW. Los resultados de este estudio, combinados con la reinterpretación de datos geológicos y fechamientos, permitieron realizar una correlación detallada de la estratigrafía volcánica de la región de Apan con las secuencias estratigráficas de rocas volcánicas en otras áreas del CVTM. Esta correlación indica que la actividad volcánica en el CVTM inició durante el Mioceno Medio.

PALABRAS CLAVE: Geología, estratigrafía, geología estructural, Apan, México Central.

ABSTRACT

The Apan region, which straddles the central and eastern sectors of the Trans-Mexican Volcanic Belt (TMVB), was geologically shaped by interrelated, intermittent tectonism and volcanism. The oldest volcanic rocks in the area were erupted about 13.5 Ma ago, followed by a nearly 10-million year volcanic hiatus. Volcanism in the area then resumed ~3.0-1.5 Ma; the most recent volcanic activity occurred in the late Pleistocene (~42-31 ka). The volcanic rocks in the Apan region range in composition from basalt to rhyolite (50-75 wt.% SiO_2) and exhibit calc-alkaline affinity; their geochemical characteristics suggest that they are subduction-zone eruptive products. Detailed geologic and stratigraphic studies using a new digital 1:100 000 scale base map for compilation of new and previous data, coupled with new K-Ar age determinations, demonstrate that the loci of volcanic centers in the region were controlled largely by a system of NE-SW-trending normal faults and associated horst-and-graben structures, resulting from a stress field with a least principal stress (σ3) oriented to the NW. Moreover, the results of this study, combined with a reexamination of geologic and age data from other investigations of the TMVB, make possible a refined correlation of the volcanic stratigraphy of the Apan region with the stratigraphic sequences of volcanic rocks in other areas of the TMVB. An important conclusion of our study is that volcanic activity in the TMVB was initiated during the Middle Miocene.

KEY WORDS. Geology, stratigraphy, structural geology, Apan, Central Mexico.

INTRODUCTION

The Apan region stradding the boundary between the central and eastern sectors of the Trans-Mexican Volcanic Belt (TMVB), is a continental andesitic-dacitic volcanic arc that extends 1200 km across central Mexico (Figure 1). Volcanism of the TMVB has been generally viewed as the result of subduction of the Cocos and Rivera plates beneath the North American plate along the Middle American Trench (MAT) (Ponce *et al.*, 1992; Singh and Pardo, 1993; Pardo and Suárez, 1993; 1995). Some authors, however, have suggested that the TMVB is related to a crustal fracture zone or to a megashear (Cebull and Shubert, 1987). More recently, Márquez *et al.* (1999) have proposed the existence of a mantle plume and the subduction of the Cocos and Rivera plates as coexisting mechanisms to explain several geochemical features of the belt. Sheth *et al.* (2000) argue against this hypothesis and proposed instead that the TMVB represents a rift-like structure that is undergoing active extension.

Recent petrological studies, particularly osmium isotopic analyses, reveal that magmatism of the TMVB involves assimilation of the lower crust (Chesley *et al.*, 2000). These results support the study of the Chichinautzin Volcanic Field (CVF) by Verma (2000), who concluded that the andesites and dacites were derived from partial melting of an heterogeneous mafic granulite in the lower crust, while the alkaline rocks crystallized from mantle-derived mafic magmas.

The timing of the onset of volcanic activity in the TMVB has been controversial as well. In the western part of the TMVB, Gastil *et al.* (1979) placed it *circa* 4.5 Ma, while Allan (1986) placed the oldest known calc-alkaline volcanism at 10 Ma. According to Mooser *et al.* (1974), volcanism in the central TMVB started 30 Ma ago, whereas in the eastern TMVB, Cantagrel and Robin (1979) suggested its beginning some 20 Ma ago. Pasquaré *et al.* (1991) found, that the oldest units in the western and central TMVB consisted of massive, fissure-vent lava flows (basaltic andesites to rhyolites) to which they assigned the general name Basal Sequence. Two samples from this sequence yielded K-Ar ages of 8.1 Ma (sample from south of Querétaro) and 7.8 Ma (sample from 15 km north of Morelia).

The TMVB is dominated by >4000 m elevation, geologically young, andesitic stratovolcanoes, some of which form short, north-south trending volcanic chains younging to the south, *i.e.*, toward the Middle America Trench. Examples are: Cántaro-Nevado de Colima-Colima, Tlaloc-Telapón-Iztaccíhuatl-Popocatépetl, and Cofre de Perote-Las Cumbres-Pico de Orizaba (see Figure 1). K-Ar data for the andesitic calc-alkaline volcanoes Sanganguey and San Juan in the western TMVB indicate that cone construction began *circa* 0.6 and 0.2 Ma, whereas in the central TMVB (Iztaccíhuatl-Nevado de Toluca) cone growth began 1.7 and 2.6 Ma ago, respectively. This age progression in the onset of growth of the andesitic volcanoes along the TMVB and the trenchward migration of volcanism are interpreted to reflect different subduction rates between the Cocos and Rivera plates (Nixon *et al.*, 1987; Pardo and Suárez, 1995; Ferrari *et al.,* 1999).

The TMVB has been divided into three sectors, each with distinctive structural, volcanic, and petrologic features (Pasquaré *et al.,* 1987). These sectors are: (1) Western sector dominated by the Colima-Chapala-Tepic triple junction, where both alkaline and calc-alkaline rocks are present. (2) Central sector characterized by rare andesitic and dacitic stratovolcanoes and silicic calderas, and a major field of monogenetic volcanism of dominantly calc-alkaline affinity. (3) Eastern sector which is characterized by andesitic-dacitic stratovolcanoes with calc-alkaline geochemical signature. Within this scheme, the Apan region straddles the boundary between the central and eastern segments, behind the volcanic front of the Sierra Nevada volcanic range composed by Telapón, Tlaloc, Iztaccíhuatl, and the active Popocatépetl volcano. Previous studies have been carried out in the Apan region, but only a few studies have focused on its volcanic stratigraphy (Ledezma-Guerrero, 1987; Castro-García and Cordoba, 1994). The most complete geological studies have dealt with the geology and evolution of the Acoculco caldera located in the north part of the area (De la Cruz-Martinez and Castillo-Hernández, 1986; Lopéz-Hernández and Castillo-Hernández, 1997). These general studies have established a good geological framework and the stratigraphic record of the area, supported by few isotopic data. In a recent publication about the palaeoenvironmental setting of the Tecocomulco lake, Caballero *et al.* (1999) reported two ^{14}C dates of organic-rich sediments underlying tephra fall deposits.

Other studies in the Acoculco area have addressed environmental and geochemical problems (De la Cruz-Martínez and Castillo-Hernández, 1986; Tello, 1986; Quinto, 1995). Some geophysical investigations using gravimetry and magnetotelluric methods have elucidated the subsurface structure of the Apan region (López-Hernández and Castillo-Hernández, 1997; Huizar-Álvarez *et al.*, 1997; Campos-Enríquez *et al.,* in press).

Although previous studies have contributed significantly to the knowledge of the surface geology and subsurface structure of the region, there are still several geological aspects that need to be clarified, including the detailed volcanic stratigraphy supported by enough isotopic dates and chemical analyses of the rocks. In this paper, we present a geological map of the Apan region that shows the distribution of the volcanic units in the area, defined by their stratigraphic position, petrographic and chemical composition, and structural features. With this new perspective, we correlate and compare the Apan region with other areas of the central and eastern TMVB. Our results allow a reexamination of the age of the onset of volcanism in this part of the belt and its tectonic implications.

METHODOLOGY

The area (Figure 1) was mapped by using a satellite image at a scale of 1:100 000 (bands 3, 5 and 7) as well as aerial photographs and topographic maps at 1:50 000 scale published by the Instituto Nacional de Geografía Estadística e Informática (INEGI). These basemap materials combined with previous work, including several regional geological maps (Ledezma-Guerrero, 1987; De la Cruz-

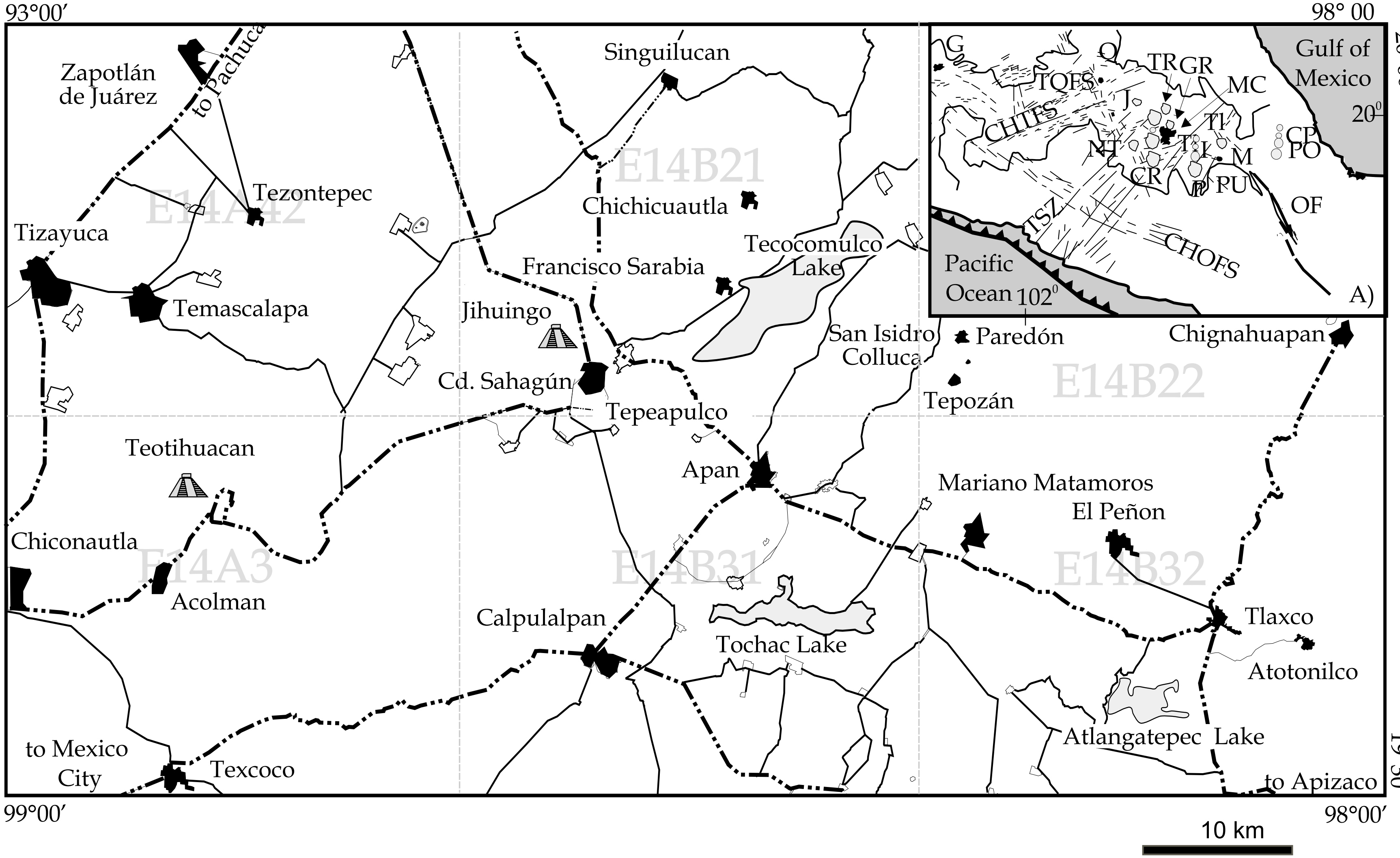

Fig. 1. The inset shows the study area with respect to the regional tectonic framework: G = Guadalajara, Q = Querétaro, MC = Mexico City, PU = Puebla. Volcanoes are: P = Popocatépetl, I = Iztaccíhuatl, T = Telapon, TL = Tlaloc, M = Malinche, PO = Pico de Orizaba, CP = Cofre de Perote, and J = Jocotitlán, TR= Tepozotlán Range, Guadalupe Range. Faults are: CHOFS = Chapala Oaxaca Fault System, CHTFS = Chapala-Tula Fault System, TQFS = Taxco-Querétaro Fault System, and OF = Oaxaca Fault.

Martínez and Castillo-Hernández, 1986; Castro-García and Córdoba, 1994; López-Hernández and Castillo-Hernández, 1997; Huizar-Álvarez *et al.,* 1997), and extensive field work were used to prepare a geological basemap at a scale of 1:50 000. Geological data were collected and compiled with the aid of these topographic maps. The topographic contour lines, geological information and cultural features were then combined into a single digital product at 1:100 000 scale. For the description of the map units we follow customary usage in published works as employed by García-Palomo *et al.* (2000a; b).

REGIONAL GEOLOGICAL SETTING

The Apan region lies between the geographic coordinates 20°00'-19°30'N, and 99°00'-98°00'W, in the states of Mexico, Hidalgo, and Tlaxcala, approximately 40 km northeast of Mexico City (Figure 1). The basement of the Apan region consists of Mesozoic limestones (Morales and Garduño, 1984), and conglomeratic red beds of Eocene age (Oviedo de León, 1970), which underlie the Miocene to early Pleistocene volcanic sequence (Ledezma-Guerrero, 1987). The geomorphology of the area is dominated by three broad plains bounded by major faults oriented NE-SW that successively drop toward the NW. These plains, from NW to SE, are referred to as Tochac, Apan, and Tizayuca respectively.

STRATIGRAPHY

Excluding the basement rocks, fifteen stratigraphic units can be recognized in the Apan region, most of them of volcanic origin. The distribution of these rocks is shown in the geological map (Figure 2), and their stratigraphic relationships are shown in Figure 3. The isotopic dates of several units are summarized in Table 1.

MIOCENE

Apan Andesite

The Apan Andesite is exposed in the northeastern and southwestern portions of the city of Apan, northwest of the city of Texcoco, and in scattered outcrops throughout the area. The outcrops typically have long narrow shapes and consist of several lava flows. The Apan Andesite was first described as "Undifferentiated Volcanic Rocks" by Ledezma-Guerrero (1987). The Apan Andesite is composed of several gray-colored lava flow units. In hand specimen, these rocks range in texture from aphanitic to porphyritic. Under the microscope, these rocks exhibit a assemblage of plagioclase, hornblende, and augite crystals set in a vitrophyric groundmass. The lava-flow units are interbedded with compact breccias and have thicknesses between 850 and 1000 m. in the vicinity of Apan.

The base of the Apan Andesite is not exposed in the area, but the unit is overlain by lava flows and scoria cones of Pleistocene age. A whole-rock K-Ar date (sample APA 84) yielded 13.4 ± 0.6 Ma, corresponding to middle Miocene. A similar date of 12 ± 0.4 Ma for this unit was obtained by López-Hernández and Castillo-Hernández (1997).

Peñon Andesite

The Peñon Andesite, which was first defined by Ledezma-Guerrero (1987), consists of complex stratovolcanoes, domes, and related pyroclastic flows. Most of the stratovolcanoes have undergone sector collapses and deep erosion. The volcanic cones of this unit have a dominantly NNE-SSW trends.

The thickness of the Peñon Andesite is difficult to determine, because it is exposed in scattered outcrops and its base is not exposed; however, Ledezma-Guerrero (1987) reported thickness ranging between 100 and 700 m. The Peñon Andesite is composed of gray andesites with fluidal textures and megacrystals of plagioclase. These lava flows are sometimes interbedded with porphyritic andesite breccias composed of phenocrysts of plagioclase and xenoliths set in a vitrophyric matrix. The Peñon Andesite underlies the basaltic lava flows of Pleistocene age and, in the region of Mariano Matamoros, underlies the Matamoros Ignimbrite.

A whole rock K-Ar date yielded an age 12.7 ± 0.6 Ma for the Peñon Andesite (García-Palomo and Macías, 2000a). Although the base of this unit is not exposed, it most likely rests on top of the Apan Andesite.

Quetzalapa Basaltic-Andesite

The Quetzalapa Basaltic-Andesite (Ledezma-Guerrero, 1987) is well exposed in the Chignahuapan valley. At this locality, the unit consists of columnar basaltic lava flows with aphanitic texture and olivine phenocrysts; in the valley of the Axaxalpa river this unit has a minimum thickness of *circa* 100 m. Here, the unit is composed of partly-altered gray lava flows with plagioclase, oriented mafic minerals and flattened vesicles. The thickness of individual lava flows averages about 60 cm. Within this sequence, there are some strongly hydrothermally altered lava flows with porphyritic textures dominated by phenocrysts of quartz and plagioclase. In the vicinity of the town of Chignahuapan, this unit is represented by basaltic-andesite lava flows with columnar jointing. Hand specimens have aphanitic textures with large flattened vesicles. This unit rests on top of the Cretaceous calcareous rocks in the Axaxalpa river and it is overlain by rocks of Pleistocene age in the same region (Ledezma-Guerrero, 1987). From field relations we infer the age of the Quetzalapa Basaltic-Andesite to be late Miocene.

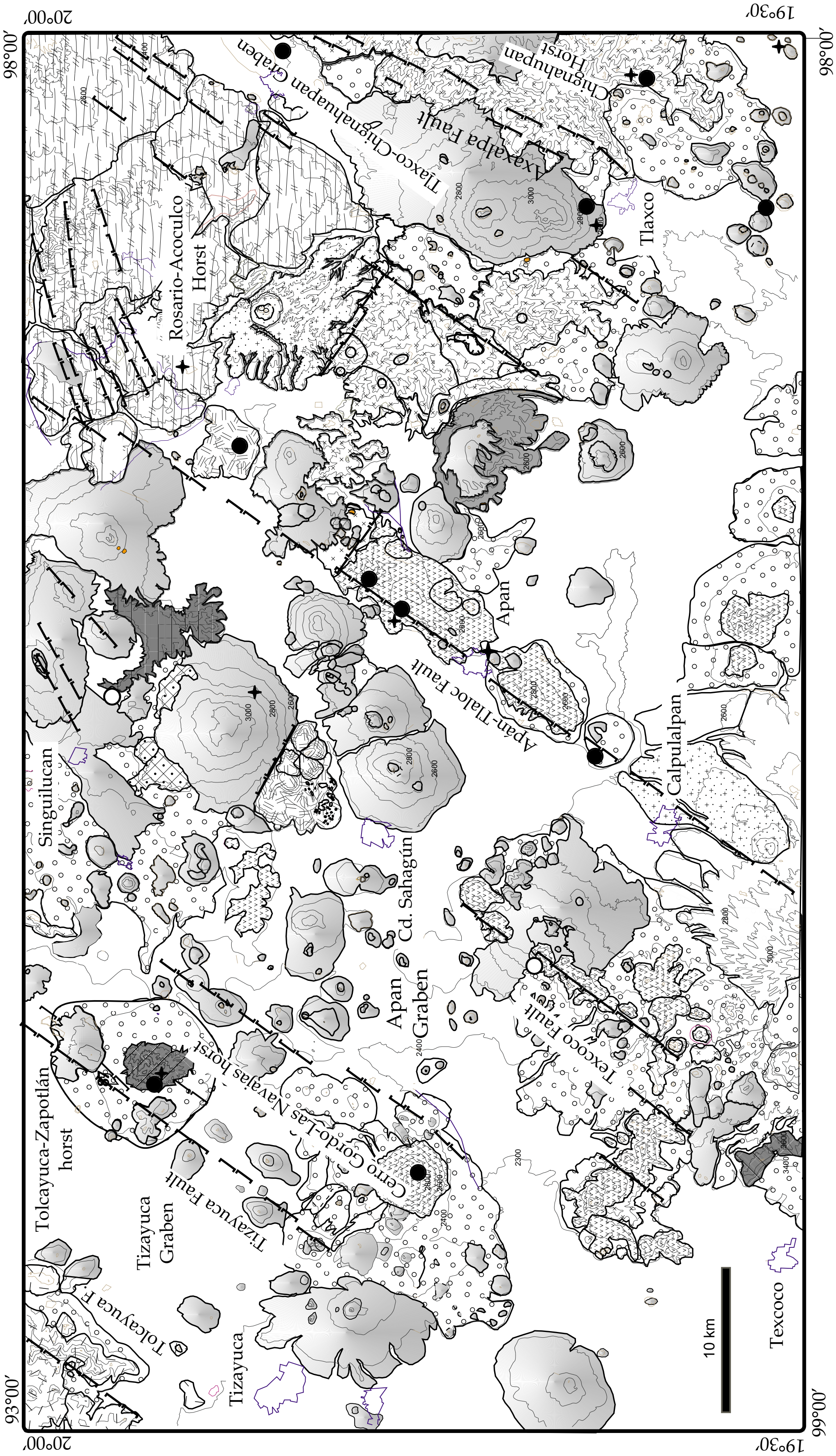

Fig. 2. Geological map of the Apan region. For names and age relations between the map units see Figure 3. Black stars K-Ar date. Black circles = chemical analyses.

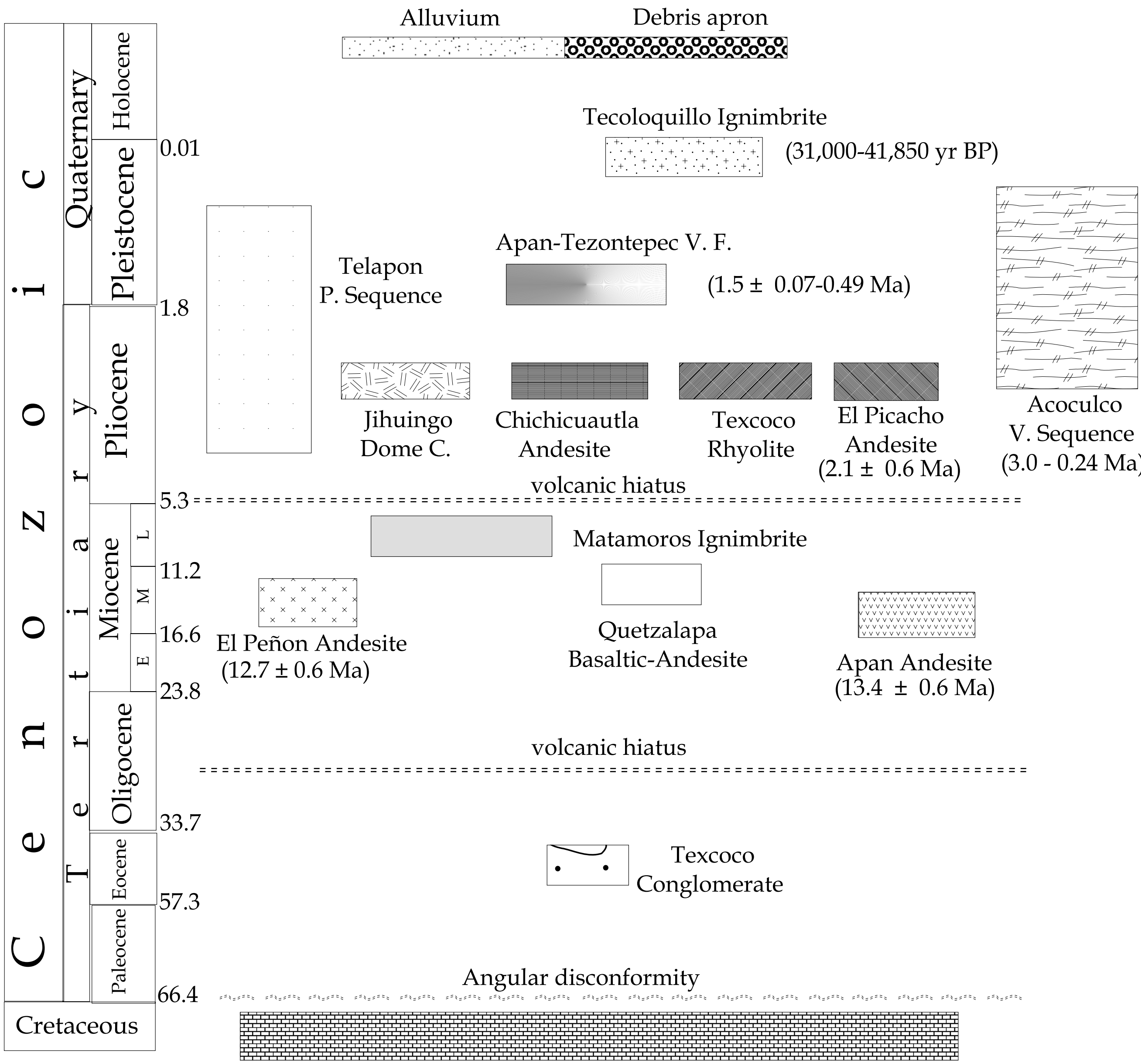

Fig. 3. Composite stratigraphic chart of the study area. Note the angular unconformity and the volcanic hiatuses throughout the regional sequence.

Matamoros Ignimbrite

In this paper, we assign the name "Matamoros Ignimbrite" to the outcrops exposed in the vicinity of the town of Mariano Matamoros. Here, this unit consists of two subunits: 1) a massive, indurated, white pumice-flow deposit that alters to pink; it has white *fiamme* and rock fragments embedded in an ash matrix rich in crystals of plagioclase, hornblende, other altered minerals, and glass; 2) surrounding the pumice-flow deposits there is a sequence composed of several light-gray hornblende dacite lava flows, each up to 2 m in thickness. The thickness of the Matamoros Ignimbrite varies from 200 to 250 m (Ledezma-Guerrero, 1987). This sequence overlies the Peñon Andesite and underlies lava flows and scoria cones of Pleistocene age. Field relationships constrain the age of this unit to the late Miocene.

PLIOCENE-PLEISTOCENE

Tlaloc Pyroclastic Sequence

This unit corresponds to the northern outcrops of Tlaloc volcano, a 4510 m high stravolcano, that forms the northernmost edifice of the Sierra Nevada volcanic chain. The Tlaloc

Table 1

Compiled radiometric dates of rocks samples of the Apan Region.

Sample	Longitude	Latitude	Unit	Rock Type	Method	Error	Age
[1]APA 84	19°45'25''	98°25'00''	Apan Andesite	Andesite	K/Ar	0.000783	*13.4 ± 0.6 Ma.
[1]APA 94	19°35'42''	98°02'09''	Peñón Andesite	Andesite	K/Ar	0.000741	*12.7 ± 0.6 Ma.
[5]AC 129	19°41'07''	98°26'20''	Apan Andesite	Basaltic Andesite	K/Ar		12.6 ± 0.4 Ma.
[5]AC 111	19°54'00''	98°15'08''	Acoculco Volcanic Sequence	Rhyolite	K/Ar		1.7 ± 0.4 Ma.
[5]AC 137	19°50'00''	98°27'09''	Apan-Tezontepec Volcanic Field	Basaltic Andesite	K/Ar		0.8 ± 0.2[5]
[1]APA 10	19°55'25''	98°45'10''	Picacho Andesite	Andesite	K/Ar	0.000120	*2.1 ± 0.1 Ma.
[2]VE116	19°38'00''	98°07'00''	Apan-Tezontepec Volcanic Field	Basalt	K/Ar		1.5 ± 0.07 Ma.
[3]U2	19°23'50''	97°58'10'	Apan-Tezontepec Volcanic Field	Basalt	K/Ar		0.47 ± 0.07 Ma.
[4]TA 3.1-3.24	19°55'05''	98°23'15''	Tecoloquillo Ignimbrite?	Sediments	C^{14}		41,850 ± 800 yr
[4]TB 2.24-2.27	19°55'00''	98°23'35''	Tecoloquillo Ignimbrite?	Sediments	C^{14}		31,000 ± 220 yr

[1]This work; [2]Cantagrel and Robin (1979); [3]Carrasco-Núñez *et al.*, 1997; [4]Caballero *et al.*, 1999. [5]López-Hernández and Castillo-Hernández, 1997.
***** analysed shows by total rock by GEOCHRON LABORATORIES, KRUEGER ENTERPRISES, INC .

sequence forms a pyroclastic fan made of massive block-and-ash flows and pumice flows interbedded with pyroclastic surges, lahars, and fallout deposits. The average thickness of this sequence is *circa* 50 m. The block and ash flow deposits contain some fumarolic pipes. In the Calpulalpan region, the Tlaloc Sequence rest on top of the Apan Andesite. This sequence is interbedded with tephra fall deposits erupted from scoria cones of late Pleistocene age. This stratigraphic relationship indicates that the age of the sequence might be as young as late Pleistocene, although the main structure of Tlaloc volcano is probably as old as Pliocene, because is cover by volcanic rocks of Pleistocene age.

On the northern slopes of Tlaloc volcano there is a volcanic structure called Yahualica, whose main structure is made of dacitic lava flows with phenocrysts of plagioclase, hornblende and quartz, embedded in a pink to gray groundmass. The volcano's apron is covered by at least 1-m of light brown massive altered pyroclastic flow deposits, and a 2m-thick massive, yellow, pumice-rich fall deposit; both of these deposits are likely associated with the volcanic activity of Tlaloc volcano. The sequence is capped by a massive light-brown lahar deposit *circa* 60 cm thick and modern soil.

Acoculco Volcanic Sequence

The Acoculco Volcanic Sequence corresponds to a caldera-like structure and related products located in the northeastern part of the study area (De La Cruz Martínez and Castillo-Hernández, 1986). This sequence includes a variety of rocks ranging from basaltic to andesitic and rhyolitic in composition (López-Hernández and Castillo-Hernández, 1997). A series of pumice flow and light-gray surge deposits are exposed in the vicinity of the town of Tres Cabezas. The surge deposits (10-70 cm thick) consist of white, rounded pumice, lithic fragments, and black obsidian set in a coarse to fine sand-size matrix. In the Paredon region, this sequence is represented by pink porphyritic dacite lava flows with quartz, plagioclase, oriented vesicles, and devitrification voids, as well as by breccias with gray and pink rhyolite clasts, pumice, and glass. At San Isidro Colluca, there are white massive pyroclastic flows deposits with angular lithic clasts embedded in a fine sand matrix.

The Acoculco Volcanic Sequence rests unconformably upon the Quetzalapa Basaltic-Andesite, and it is capped by the Tecoloquillo Ignimbrite and lava flows of Pleistocene age (Ledezma-Guerrero, 1987). The age of this sequence ranges from 3.0 to 0.24 Ma (Pliocene to Pleistocene) (López-Hernández and Castillo-Hernández, 1997).

Chichicuautla Andesite

Ledezma-Guerrero (1987) described a caldera-like structure near the town of Singuilucan, Hidalgo, that he named "Chichicuautla Caldera". This structure is exposed in the northern portion of our study area; it has a half-moon shape 6 km in diameter and stands 250 m elevations relative to above the surrounding terrain. In this paper, we refer to all rocks associated with this structure as the Chichicuautla Andesite. It consists of a series of gray, porphyritic andesitic lava flows, with phenocrysts of plagioclase and hornblende embedded in a red, hydrothermally altered, aphanitic matrix. In the southern portion of the caldera structure, there is an heterolithologic debris avalanche deposit composed of hydrothermally altered lithic clasts with jigsaw-puzzle structures. The thickness measured from the highest point to the base of this structure is approximately 300 m.

The Chichicuautla Andesite overlies the Miocene rocks north of the town Singuilucan and is overlain by lava flows of Pleistocene age in the Francisco Sarabia community. Because of these stratigraphic relationships, we consider this unit to be of Pliocene age.

Texcoco Rhyolite

In this work, we refer to the rocks forming a semi-circular caldera-like structure located 5 km west from the City of Texcoco as the "Texcoco Rhyolite". This unit consists of several pink compact lava-flow units, each approximately 5 m in thickness. In hand specimen, these rocks, which are composed of quartz, plagioclase and abundant xenoliths, exhibit a banded texture with white and pink stripes. Under the microscope, they consist of subhedral to anhedral phenocrysts of plagioclase, amphibole and pyroxene set in a groundmass of plagioclase, oxides and glass. The thickness of this unit is approximately 250 m.

This sequence is overlain by the Apan-Tezontepec Volcanic Field, and it probably rests on top of the older rocks of the Tlaloc Pyroclastic Sequence. These relationships indicate that the Texcoco Rhyolite is older than Pleistocene and likely of Pliocene age.

Picacho Andesite

The Picacho Andesite is a highly eroded dome structure dissected by abundant fractures and normal faults. It is exposed in the western edge of the study area, where it reaches a thickness of 600 m. At this location, the main part of the sequence consists of gray andesitic lavas interbedded with a debris avalanche and block-and-ash flow deposits. The debris-avalanche deposit is made up of gray andesite blocks with fluidal structure and aphanitic texture.

The dome structure is surrounded by lava flows and fluvial deposits. The basal contact of the andesite is not exposed and it is overlain unconformably by lava flows of Pleistocene age. In this work, we report a whole rock K-Ar age of 2.1 ± 0.1 Ma for the Picacho Andesite, which places it within the late Pliocene.

Jihuingo Dome Complex

First described as the Jihungo Dome by Ledezma-Guerrero (1987), this structure is actually more complex, because it is composed of five domes aligned in an E-W direction. The dome-forming rocks are light-gray andesites, with aphanitic textures, and aligned vesicles. Associated with these domes is a debris-avalanche deposit with main dispersal axis to the south. The debris-avalanche deposit has hummocks with internal structures consisting of vesicular, black andesites with aphanitic textures and jigsaw puzzle structures. Because the Jihuingo Dome Complex is capped by lava and pyroclastic rocks of Pleistocene age, we assign it to the Pliocene.

Apan-Tezontepec Volcanic Field

A NNE-SSW-trending volcanic field consisting of roughly 280 scoria cones, 10 shield volcanoes, 5 domes, and multiple lava flows are exposed between the towns of Tezontepec and Tlaxco. In this paper, we propose the name Apan Tezontepec Volcanic Field (ATVF) for these landforms. The rocks forming the ATVF are essentially gray to brown basaltic-andesites with aphanitic textures and phenocrysts of olivine and plagioclase.

The lava flows have oriented vesicles as well as other flow structures, and they are interbedded with volcanic breccias and pseudolaminar fallout deposits that consist of interbedded layers of black sand-size scoria and ash.

The ATVF commonly unconformably blankets the older units in the area. Three radiometric dates of 1.5 ± 0.07 Ma (Cantagrel and Robin, 1979), 0.8 ± 0.2 Ma (López-Hernández and Hernández-Castillo, 1997), and 0.47 ± 0.07 Ma (Carrasco *et al.,* 1997) place this unit in the Pleistocene.

PLEISTOCENE–HOLOCENE

Tecoloquillo Ignimbrite

The Tecoloquillo Ignimbrite includes the Tecoloquillo volcano, a 400 m-high structure located in the northeastern part of the area. It is composed by a central rhyolitic dome nested within a 0.6 km-wide crater and surrounded by an apron of pyroclastic flow deposits. The rocks forming the central dome are pink, phorphyritic massive rhyolites composed of quartz, feldespar and hornblende embedded in a glass-rich groundmass. The pyroclastic apron consists of white, massive, block-and-ash flow deposits as great as

50 m thick. Individual deposits consist of light-gray lithic clasts embedded in a coarse to medium sand-size matrix rich in crystals of quartz and plagioclase. While the rocks of this volcano rest unconformably on the Miocene Peñon Andesite. Their age is still unknown. Caballero *et al.* (1999) described two young tephras (~41 850 ± 800 and ~31 000 ± 220 yr. B. P.) in the Tecocomulco lake, which they proposed to be related to the activity of the Tecoloquillo volcano or the Acoculco caldera. If their suggestion should prove to be correct, then the Tecoloquillo Ignimbrite would be of late Pleistocene age.

Alluvial deposits and debris aprons

These deposits represent the youngest deposits in the area. They dominate the flat plains of the Tizayuca, Apan, and Tochiac basins. The central part of the basins is commonly filled by lacustrine deposits, one of which contains the modern lake of Tecocomulco northeast of the City of Apan. This lake preserves a stratigraphic record of 50 000 yr BP with continuous lacustrine sedimentation interrupted by tephra-fall deposition from the nearby volcanoes (Caballero *et al.*, 1999). Other lakes are the Tochac and Atlangatepec located in the eastern part of the study area.

WHOLE-ROCK CHEMISTRY

Ten samples were analyzed by the X-ray fluorescence at the Laboratorio Universitario de Geología Isotópica (LUGIS), UNAM. Five samples were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) and instrumental neutron activation analysis (INAA) (<0.01% major and trace elements; Ba, Cr, Cu, Ni, Sr, Ta, V, Y, Zn, and Zr < 1 ppm; Cs, Hf, Tb, U and Th = 0.5 ppm; Rb, 20 ppm; Sm, Eu and Yb=0.1 ppm; detection limits) at Activation Laboratories, Ancaster, Canada. The results are listed in Table 2.

The composition of these rocks ranges from basalt to rhyolite (50-75 wt.% SiO_2) in the TAS diagram of Le Bas *et al.* (1986) (Figures 4A). The oldest rocks of the area, belonging to the Miocene El Peñón and Apan Andesites (samples APA-79, APA84, and APA-94), have silica concentrations between 60 and 62 wt.%, and fall within the medium K field of the SiO_2 vs. K_2O diagram (Figures 4A-B). The Pliocene Picacho Andesite and Chichicuautla rocks (APA-10, AC-19, AC-17, and APA 176) have silica concentrations ranging from 55 to 59 wt.%, and fall mainly in the medium K field of the SiO_2 vs. K_2O diagram (Figure 4a-b). The AVC rocks (APA-101, AC 40, AC49, and AC33) are easily distinguished from the rest since they are rhyolites with high silica contents >70 wt.% and high K concentrations (Figure 4A). The ATVF rocks (APA 163, APA-99, APA-93 APA-85, APA-78, APA-76, and AC32) are basaltic-andesites with silica contents between 50 and 56.5 wt.%. (Figure 4B).

Figure 4c show the multi-element diagram normalized with respect to the primordial mantle (Wood, 1979). It has a typical calc-alkaline pattern enriched in LILE elements with respect to the HFSE and a negative Ti, NbP, anomaly. These geochemical characteristics suggest that magmas erupted in the Apan region are subduction-related eruptive products.

STRUCTURAL GEOLOGY

The rocks of the Apan region are affected by several fault and fracture systems. The Apan area is located within the northeastern tip of the Tenochtitlan Shear Zone, a major fault system that extends from Petatlán, Guerrero, southern Mexico to the states of Tlaxcala and Hidalgo in central Mexico (De Cserna *et al.,* 1988). There are several expressions of faults in central Mexico that have a general NE-SW orientation. Flores (1978) described a major NE-trending fault in the area surrounding Nevado de Toluca. Scheidegger (1979) noted a preferential joint orientation of N34°E in Central Mexico. Sandoval (1985) recognized a NNE fault structure that runs from the inner slope of the Middle American Trench to the Trans-Mexican Volcanic Belt. Lara-Sánchez and Salinas-Prieto (1999) described a NNE fracture system in the Zihuatanejo region, which they interpreted as a zone weakness corresponding to the suture zone of the Zihuatanejo subterrane. Recently, García-Palomo *et al.* (2000c) described three fault systems in the Nevado de Toluca region; one these, the San Antonio system, has a NE orientation with a horst-and-graben geometry. In the Apan region, this NE trending fault system is represented by several major faults, including the Tizayuca, Texcoco, and Tolcayuca faults (this work), the Apan-Tlaloc fault (Mooser and Ramírez, 1987; Huizar-Álvarez *et al*., 1997; Campos-Enríquez *et al.,* in press) and Axaxalpa fault (De la Cruz-Martínez and Castillo-Hernández, 1986). As a group, the orientation of these structures is mostly NNE-SSW, with dips to the west and east between 60° and 90°. Associated with these faults are several minor faults.

Several lines of evidence, including cinder-cone alignments, slickensides, gravimetry, fracture trends and primary structures orientations suggest that these normal faults have a graben-and-horst geometry. The horsts are: Chignahuapan, Rosario-Acoculco, Cerro-Gordo-Las Navajas y Tolcayuca-Zapotlan, while the grabens are: Tlaxco-Chignahuapan, Apan and Tizayuca. This structural geometry results from a stress field with regime σ3 oriented to the NW and σ1 oriented vertically (García-Palomo and Macías, 2000a). This extensional tectonics regime has created a se-

Table 2

Whole-rock chemical analyses of major, trace, and rare-earth elements of rocks of the Apan region.

Sample	**APA10**	**APA76**	**APA78**	**APA79**	**APA84**	**APA85**	**APA93**	**APA94**	**APA99**	**APA101**	***APA132**	***APA163**	***APA175**	***APA176**
Wt. %														
SiO_2	56.40	55.61	55.97	61.30	60.07	52.27	50.02	60.52	54.34	75.61	57.44	52.83	54.13	60.60
TiO_2	1.268	0.978	0.969	0.93	0.79	1.42	1.50	0.68	0.91	0.13	1.04	1.51	1.14	0.74
Al_2O_3	16.39	17.78	18.35	16.57	18.21	17.21	17.10	18.85	16.73	12.66	19.01	17.12	15.69	17.06
Fe_2O_3t	7.77	6.77	6.34	6.12	5.49	7.94	9.29	50.40	7.15	1.36	6.51	8.97	8.35	4.79
MnO	0.12	0.103	0.101	0.086	0.087	0.11	0.14	0.08	0.10	0.04	0.09	0.13	0.13	0.06
MgO	3.96	5.19	4.57	3.98	2.82	6.41	7.13	2.57	7.02	0.18	3.41	5.90	7.62	2.60
CaO	6.81	7.89	7.73	5.53	6.14	8.74	10.05	6.26	7.54	0.36	6.96	8.06	7.93	5.47
Na_2O	3.76	3.64	3.62	3.22	4.23	3.52	3.26	4.08	3.81	3.82	4.25	3.56	3.65	4.05
K_2O	2.22	1.20	1.38	1.43	1.30	0.93	0.88	1.24	1.20	4.86	1.12	1.55	1.28	1.81
P_2O_5	0.646	0.236	0.188	0.21	0.25	0.36	0.31	0.18	0.23	0.006	0.21	0.38	0.36	0.16
PXC	0.28	0.15	0.4	0.53	0.73	0.41	0.7	0.5	0.48	0.54	0.24	0.36	-0.15	1.39
Total	99.64	99.56	99.64	99.96	100.15	99.36	100.41	100.39	99.56	99.61	100.30	100.4	100.15	98.73
ppm														
Ba	592	449	316	533	399	274	251	299	295	59	377	429	459	826
Rb	37	19	25	36	24	12	12	25	17	161	22	23	31	32
Sr	477	553	445	368	1217	731	443	856	599	4	541	564	656	585
Y	31	17	17	23	15	17	19	12	12	52	19	30	25	30
Th	5	6	<2	7	3	3	3	4	<2	22	1.5	2.3	3	4.1
Pb	9	9	5	9	6	3	4	7	4	22	<3	<3	<3	<3
Zn	95	64	67	78	64	75	57	63	76	62	69	83	87	57
Cu	<0.7	14	3	6	14	19	50	62	12	7	13	19	24	11
Ni	36	79	57	42	32	120	106	40	191	20	11	57	157	154
V	114	133	131	106	83	167	177	95	170	3	119	175	151	71
Cr	50	116	34	128	13	183	159	18	393	4	50	130	260	79
Hf											3.2	5	5.2	5.3
Cs											-0.2	0.8	0.6	0.6
Sc											16.5	21.8	21.2	11.8
Ta														
Co	37	38	69	44	32	71	53	41	59	32	15	28	32	13
Be											1	2	1	1
U											0.3	0.7	0.9	1.1
W														
Mo														
Au														
Zr	342	170	142	200	167	176	150	152	133	206	132	242	244	206
La											13	27.3	28.4	28.4
Ce											27	52	56	47
Nd											16	30	31	22
Sm											3.4	6.2	6.1	4.5
Eu											1.2	1.7	1.75	1.4
Tb											0.5	0.8	0.7	0.7
Yb											1.83	2.82	2.27	2.25
Lu											0.27	0.41	0.34	0.40

Samples analysed by LUGIS laboratory UNAM, Mexico, and Activation Laboratories Ltd., Ancaster, Canada.

ries of stepped mountain blocks tilted toward the E and SE. This geometry defined the three major plains between blocks, each plain separated from the other by 100 meters of relief. These plains have been the locus of lacustrine (e.g., Tecocomulco lake) and subaerial sedimentation. Strikingly, the Miocene rocks of the region have the same aerial distribution pattern as the main faults of the area, for instance, the Apan and El Peñón Andesites. A similar alignment is observed among the scoria cones of the ATVF and the Telapón and Tlaloc volcanoes, suggesting that these volcanic

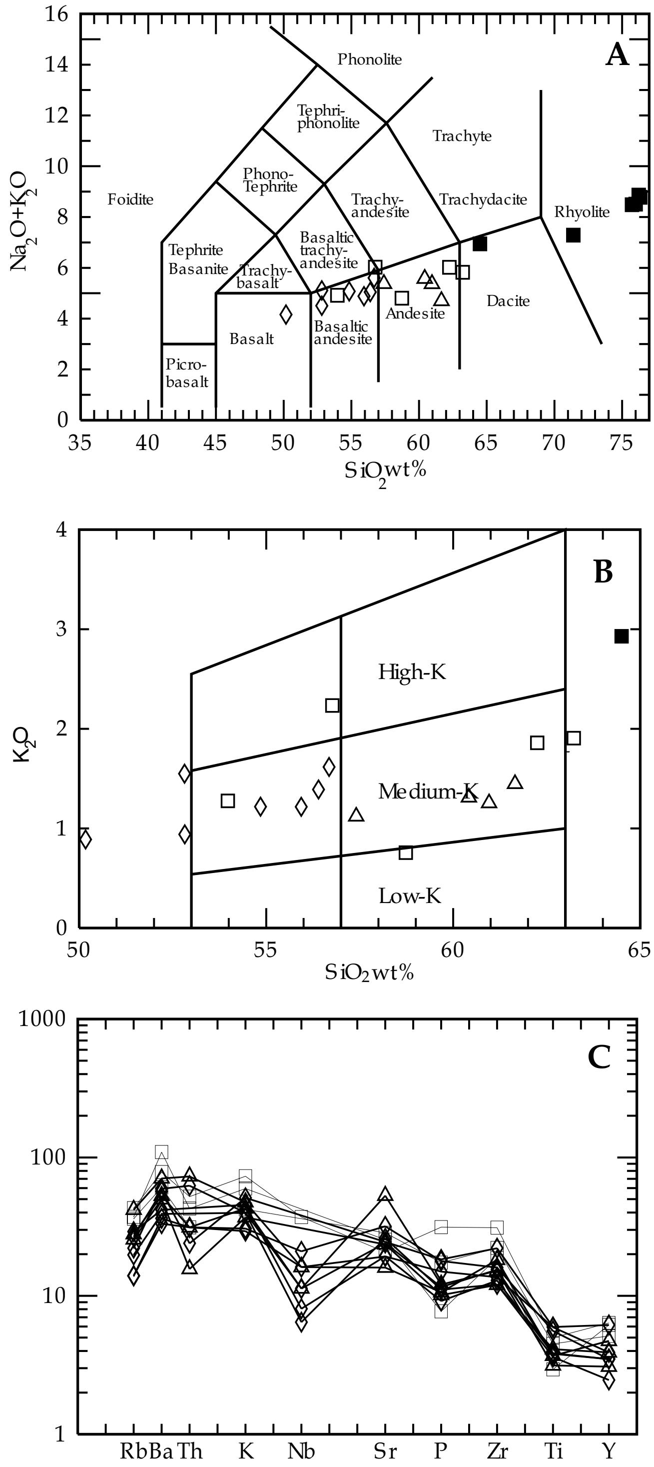

Fig. 4. A) SiO_2 versus alkali diagram of the rocks of the Apan region. Normalization 100% LOI free (Le Bas *et al.*, 1986). B) K_2O-SiO_2 classification diagram after Peccerillo and Taylor (1976), most rocks from the Apan region fall within the K-medium field. C) Multi-element diagram that shows all the rocks of Apan region. Normalized values according to Wood (1979). Open Triangle = Miocene rocks. Open square = Pliocene rocks. Filled square = Acoculco Volcanic Sequence. Open diamond = Apan Tezontepec Volcanic Field.

structures envolved along with these major faults since the middle Miocene.

GEOLOGICAL EVOLUTION

Geological mapping supported by radiometric dating of the principal units allows us to reconstruct the geological evolution of the Apan area. New isotopic dates, along with previous published dates, are plotted in an histogram of rocks vs. frequency (Figure 6). The histogram suggests several *hiatuses* separated by frecuency peaks that we interpret as volcanic gaps and periods of intense volcanic activity, respectively. We tested this interpretation with the known geologic record from the eastern and central parts of the TMVB (Figure 7). According to this correlation chart (Figure 7) it is feasible to infer that the Apan region and the rest of Mexico were covered by a marine transgression, which begun during the Jurassic and continued until the Cretaceous time during which thick marine calcareous sediments were deposited. During the latest Cretaceous-earliest Paleogene, the sea withdrew during the uplift caused by the Laramide Orogeny (Coney 1989). This orogenic event caused uplift and developed a prominent unconformity between marine and continental rocks. In the Apan region the unconformity is represented by a gap recognized in the Texcoco well site (Oviedo de León, 1970) located few kilometers west of the study area. In this well, the Eocene rocks of the Texcoco conglomerate, which is correlated with Balsas Group (Fries, 1956), which overlie along an angular unconformity the Cretaceous calcareous rocks. After the Eocene no volcanic activity occurred in the region until the middle Miocene. The second volcanic hiatus recorded in the area in the Chignahuapan range, exposes rocks of middle Miocene age overlying unconformable calcareous Mesozoic rocks. This volcanic gap has been considered the transition between volcanism of the Sierra Madre Occidental (SMO) and the early stage of volcanism in the TMBV (Venegas *et al.*, 1985; Garduño-Monroy and Gutiérrez-Negrín, 1992). During the middle Miocene, andesitic volcanoes and associated domes aligned in a NNW-SSE direction were built in the Apan region. These volcanic structures developed collapse structures as well as avalanche, and pyroclastic deposits. At the same time, two lava plateaus, represented by the Apan Andesite and Quetzalpa Basaltic-andesite, were formed by eruptions through vent fissures oriented NNE-SSW. During the latest Miocene, volcanic activity ended with the emplacement of felsic volcanic complexes, which produced the thick sequence of pyroclastic flows and dacitic lava flows of the Matamoros Ignimbrite. The geochemical signatures of the Miocene rocks indicate that they were produced by magmatism related to an orogenic setting suggesting that during Miocene a volcanic arc existed in western Mexico. Therefore, the rocks exposed may well represent the early stages of the TMVB in the region. From to the areal distribution of these rocks in the Apan area, together with

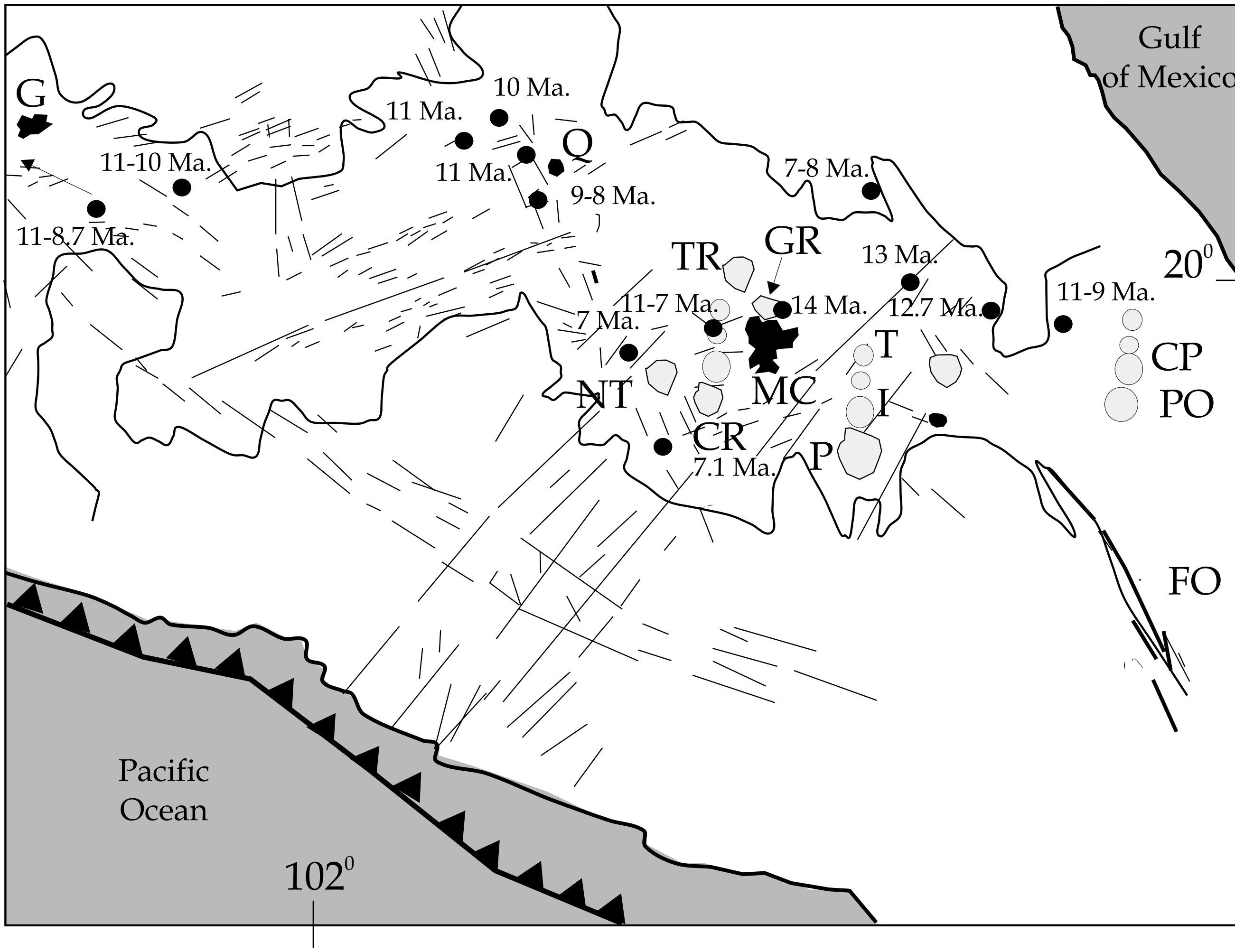

Fig. 5. Localities (filled circles) of dated Miocene rocks in the TMVB. After Carrasco-Núñez *et al.*, 1989; Pérez-Venzor *et al.*, 1996; Valdez-Moreno *et al.,* 1998; Gómez-Tuena and Carrasco-Núñez, 2000; García-Palomo *et al.*, 2000 c; Yánez-García and Durán-García, 1982; Ferrari *et al.,* 1994; 2000; Jacobo-Albarrán, 1985; Lozano-Barraza, 1968. Letter symbols same as in Figure 1.

new statigraphic evidence supported by isotopic dating, we believe that our study supports the idea of previous authors who have considered the middle Miocene as the initiation time for the formation of the TMVB. This is important because the early stages of formation of the TMVB have been a matter of controversy for decades among authors who have considered it as Oligocene (Mooser, 1969), Miocene (Cantagrel and Robin, 1979), Pliocene (Gastil *et al.*, 1979), and even as young as Quaternary (Demant and Robin, 1975). However, recent studies have reported new dates and localities of specific volcanoes in the TMVB, for example, Zamorano volcano 10 Ma (Carrasco-Núñez *et al.*, 1989), Palo Huérfano volcano 11 Ma (Pérez-Venzor *et al.*, 1996), La Joya volcano 11 Ma (Valdéz-Moreno *et al.,* 1998), Cerro Grande volcano 11-9 Ma (Gómez-Tuena and Carrasco-Núñez, 2000), San Antonio volcano > 7.1 Ma (García-Palomo *et al.*, 2000 c). Alseseca Andesite 11 Ma (Yánez-García and García-Duran, 1982), the lava plateaus in Nayarit 11-8.7 Ma, Jalisco-Guanajuato 11-10 Ma, Querétaro 9-8 Ma, and Hidalgo 7-8 Ma (Ferrari *et al.* 1994; 2000), as well as the Basal Sequence around Nevado de Toluca 7.1 Ma. (García-Palomo *et al.*, 2000 c). Moreover, other volcanic structures in the Mexico basin have similar older ages, such as the Las Tres Cruces mountain with dates between 11 and 7 Ma, the Tepozotlán range from 13.2-14.1 Ma (Jacobo-Albarran, 1985), and the dacitic domes of the Guadalupe range from 13 to 14 Ma (Lozano-Barraza, 1968) (Figure 5). The two new dates for Miocene rocks of El Peñón Andesite 12.7 Ma and the Apan Andesite 13.4 Ma along with all these dates strongly support the idea that activity in the TMVB began during the Miocene (Moran-Zenteno *et al.*, 1998; Ferrari *et al.*, 1994; Garduño-Monroy and Gutiérrez-Negrín, 1992).

As evidenced from the regional stratigraphy (Figures 3,7), an important unconformity and hiatuses separate the Miocene volcanic rocks from the rest of the sequence. The unconformity and hiatuses were recognized and correlated with other areas in the central and eastern parts of the TMVB

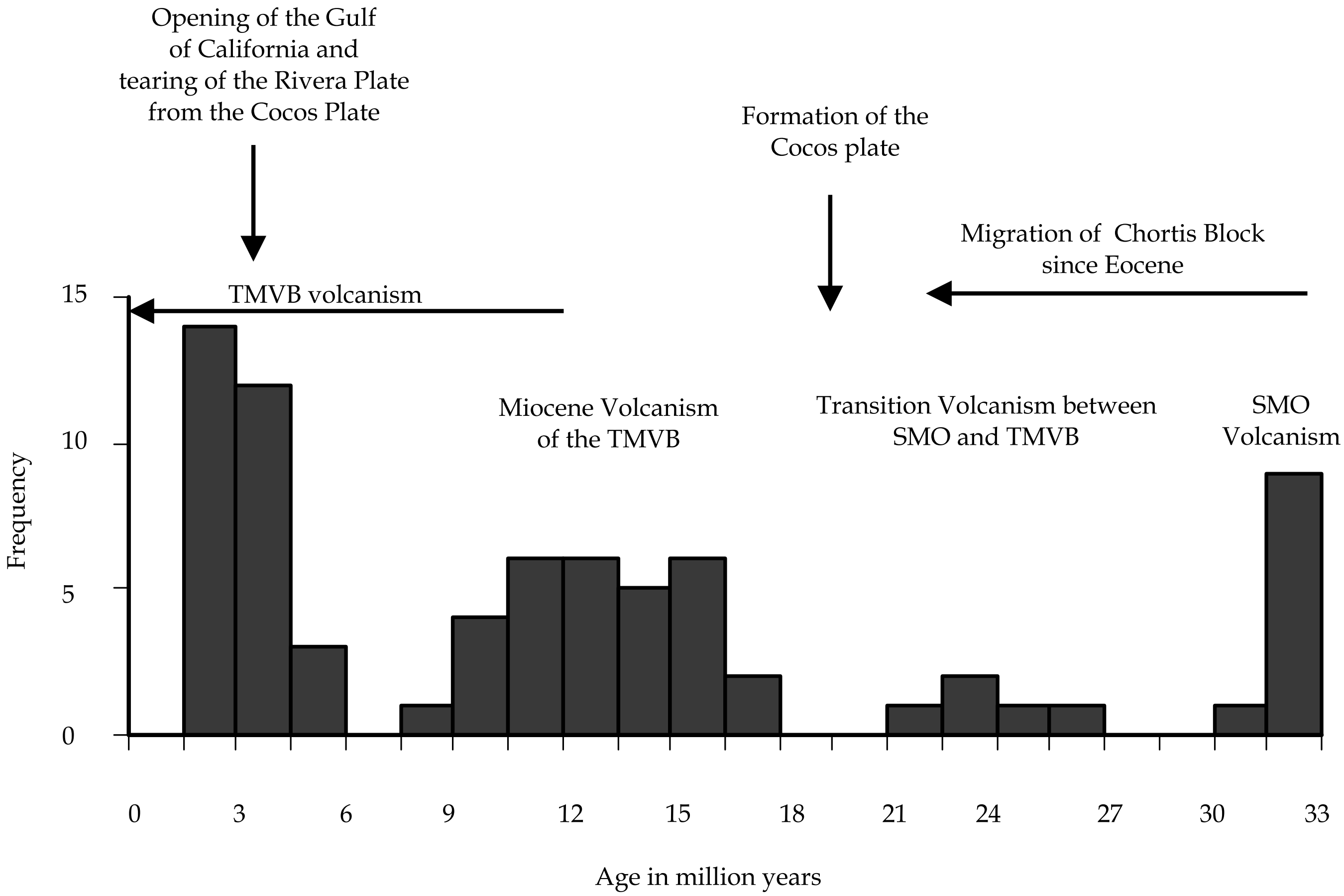

Fig. 6. Age vs. frequency plot, that shows the main gap and frequency peaks interpreted as main phases of volcanic activity, tectonics, and hiatus (Atwater, 1970; Mammerickx and Klitgord, 1982; Schilt and Karig 1982). TMVB=Trans-Mexican Volcanic Belt; SMO= Sierra Madre Occidental.

(Figure 6), and by compiling a large isotopic data set (see Table 2, and Figure 7). After this hiatus an accumulation peak of volcanism appears that is related to the beginning of the activity of the TMVB during the middle Miocene. During this time important stratovolcanoes and lava plateaus were emplaced with an orientation very similar overall to the TMVB (Ferrari *et al.*, 1994; Garduño-Monroy and Gutiérrez-Negrín, 1992.).

During the Pliocene, subduction processes in southwestern Mexico again produced widespread volcanism. The activity first began at Tlaloc volcano, which is the northern tip of the Sierra Nevada Range. This volcano was built progressively, first upon the eruption of lava flows followed by the emplacement of pyroclastic flows and, finally, by extrusion of a summit dome. At the same time, the Acoculco caldera was developed in two main episodes. The first episode, between 3 and 2.6 Ma, generated several domes emplaced on annular fractures approximately 34 km in diameter (López-Hernández and Castillo-Hernández, 1997). The second episode, which occurred between 1.7 and 1.26 Ma involved the emplacement of dacitic and rhyolitic domes followed by the emplacement of pyroclastic flows and associated caldera collapse. The activity at Acoculco caldera ended *circa* 0.24 Ma with the eruption of basaltic-andesite lava flows (López-Hernández and Castillo-Hernández, 1997). In contrast, during the Pliocene, the Chichicuautla Andesite and Texcoco Rhyolite were formed by strong explosive eruptions that produced pyroclastic flows and avalanche deposits. The Picacho and Jihuingo Complexes Domes also were passively extruded during this time. The first one was emplaced along NNE-SSE fault zones, while the second was emplaced a long an E-W trending fault. The complex growth of the two domes uncluded the partial collapse of the dome complex with the generation of debris-avalanche deposits. During the Pleistocene, the explosive activity formed monogenetic volcanoes named the Apan Tezontepec Volcanic Field producing about 280 monogenetic volcanoes. This activity occurred between 1.8 Ma and 0.47 Ma, during which time there also occurred a change in the structural regime in the area, because the volcanisms was localized along fractures associated with a horst-and-graben geometry with a extension di-

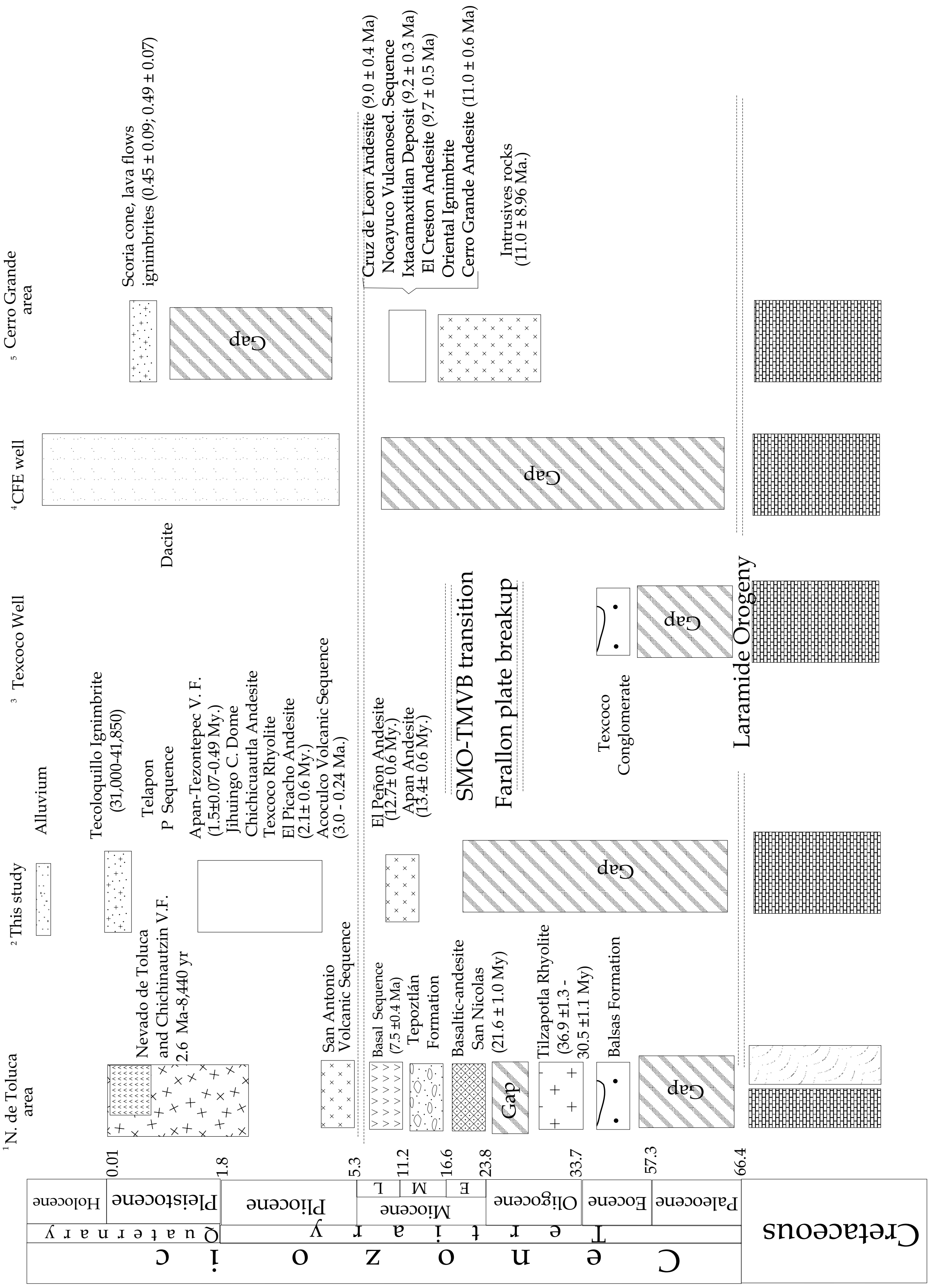

Fig. 7. Stratigraphic correlation chart for volcanic and related rocks of the Apan region and other areas within the central and eastern portions of the Trans-Mexican Volcanic Belt. References are: [1]García-Palomo *et al.* (2000c), [2]This study, [3]Oviedo de León (1970), [4]López-Hernández and Castillo-Hernández (1997), and [5]Carrasco-Núñez (1997).

rection toward the NNW. This modification in the stress field structural regime produced mountains ranges defined by blocks stepping to the NW. During the late Pleistocene, volcanism began to wane, represented only by activity that built Tecoloquillo volcano. The younger hiatus is clearly re-corder in the well drilled by Comisión Federal de Electricidad (Federal Commission of Electricity) in the Acoculco Caldera region (Lopez-Hernández-Castillo-Hernández 1997). Here, the rocks of Pliocene age rest unconformably on Cretaceous calcareous rocks. We consider this hiatus as the same unconformity demostrated by our isotopic dating studies in the region. This hiatus, which was interpreted as resulting from the geodynamic reorganization of the Pacific margin during this time (Garduño-Monroy and Gutiérrez Negrín, 1992), is separated by a frecuency peak around 3 Ma (Figure 6). This peak is related to the main eruptive phases of the TMVB, during which most of the stratovolcanoes in central Mexico, such as Nevado de Toluca, began to form (García-Palomo, 2000c).

CONCLUSIONS

Detailed mapping in the Apan region, coupled with stratigraphic and dating studies indicate that volcanism in the area began about 13 Ma. This date is compatible with data for others volcanic centers for the initiation of the volcanic activity in the TMVB during middle Miocene. The activity culminated with the development of stratovolcanoes and lava plateaus. Several aspects of the volcanism including, eruptive style (effusive vs. explosive), mode of occurrence (lava plateau vs. stratovolcanoes), and petrologic-geochemical signatures evolution (different degrees of magma evolution), indicate that during the middle to late Miocene the process of convergence along the Pacific margin was very complex. During the Pliocene, intense volcanic activity also took place in the TMVB, producing the domes, stratovolcanoes, and cinder cones of the Apán-Tezontepec Volcanic Field (ATVF). The area was affected by several normal faults with main trends oriented NNE-SSW, dipping toward the NW and SE. These faults are inferred to have served as magma pathways, as suggested by the orientation of rocks with the same alignment throughout the area. Additionally, the aereal distribution of volcanic map units also suggest that these faults might have been reactivated periodically through time.

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