

Volcanic and tectonic evolution of central Mexico: Oligocene to present

Luca Ferrari^{1,3}, Victor Hugo Garduño², Giorgio Pasquarè¹ and Alessandro Tibaldi¹

¹ *Dipartimento di Scienze della Terra, Università di Milano, Milano, Italia*

² *Departamento de Geología, Universidad Michoacana San Nicolás de Hidalgo, Morelia, Mich., México*

³ *Also at: Departamento de Exploración, Gerencia Proyectos Geotermoeléctricos, Comisión Federal de Electricidad, Morelia, Mich., México*

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RESUMEN

Con base en una síntesis de datos geocronológicos, estratigráficos y estructurales de los terrenos volcánicos de México, re-construimos las relaciones espacio-temporales entre la Sierra Madre Occidental (SMO) y la Faja Volcánica Trans-Mexicana (FVTM). Un análisis de 520 edades radiométricas integradas con los datos geológicos disponibles muestra que la migración del volcanismo predominantemente silícico del arco de la SMO con orientación NNW, al arco intermedio a máfico de FVTM con orientación E-W, ocurrió gradualmente en respuesta al progresivo desarrollo de la trinchera de Acapulco durante el Mioceno Temprano y Medio. Durante la mayor parte del Oligoceno, el arco de la SMO se desarrolló en un cinturón amplio con orientación NNW hasta la longitud de la ciudad de México al este y hasta la actual trinchera de Acapulco hacia el sur. Al final del Oligoceno y principios del Mioceno, el frente volcánico se situó a 230 km de la trinchera, aunque el resto del arco mantuvo la misma localización. Se piensa que este cambio refleja el desarrollo progresivo de la trinchera actual, en el sitio de la antigua frontera transforme entre la placa Norteamericana y el bloque Chortis. En el Mioceno Medio, los productos intermedios y máficos fueron emplazados a lo largo de un cinturón con orientación general E-W, extendiéndose también al este de la ciudad de México, mientras que en el Mioceno Tardío este volcanismo asumió un carácter uniformemente basáltico y una amplia distribución. La orientación general del arco no ha cambiado desde hace 16 Ma al presente, aunque se observa una migración del frente volcánico hacia la trinchera. Basados en la orientación general del arco y en la composición dominante de los productos volcánicos, proponemos que la FVTM comenzó hace aproximadamente 16 Ma cuando empezó a formarse un arco volcánico intermedio a máfico con una orientación general E-W.

La evolución tectónica de las partes occidental y central de la FVTM está caracterizada por una fase Mioceno Medio de fallamiento transcurrente seguida de una fase transtensional y extensional entre el Mioceno Tardío y el presente. La deformación se concentra en una zona con tendencia NW-SE en la parte occidental y en una zona amplia de 50-70 km orientada E-W en la parte central de la FVTM. La coincidencia entre el inicio de la FVTM y la fase de fallamiento transcurrente nos lleva a proponer que las fallas transcurrentes NW-SE y E-W podrían haber provisto vías preferenciales al magma cortical, permitiendo la formación de la FVTM con su orientación oblicua con respecto a la trinchera.

PALABRAS CLAVE: Geocronología, edades radiométricas, estratigrafía, estructura, evolución tectónica, terrenos volcánicos, Sierra Madre Occidental, Faja Volcánica Trans-Mexicana.

ABSTRACT

Based on a synthesis of geochronologic, stratigraphic, and structural data of the volcanic terrains of central Mexico we reconstruct the spatial and temporal relations between the Sierra Madre Occidental (SMO) and the Mexican Volcanic Belt (MVB). An analysis of 520 radiometric ages integrated with the available geological data shows that the migration of volcanism from the NNW trending, dominantly silicic SMO arc to the roughly E-W trending intermediate to mafic MVB arc occurred gradually in response to the progressive development of the Acapulco trench in early to middle Miocene times. During most of the Oligocene the SMO arc developed in a broad NNW trending belt up to the longitude of Mexico City and as far south as the present Acapulco trench. In latest Oligocene and early Miocene times the volcanic front receded about 230 km from the trench while the rest of the arc retained the same location. This change is thought to reflect the progressive development of the present trench, at the site of the former transform boundary between the North America plate and the Chortis block. In middle Miocene times, intermediate to mafic volcanic products were emplaced along a rough E-W trending belt extending also east of Mexico City, while in late Miocene this volcanism assumed a uniform basaltic character and a widespread distribution. The overall orientation of the arc did not change since 16 Ma to the Present although a trenchward shifting of the volcanic front is observed. Based on the overall orientation of the arc and on the dominant composition of the volcanic products, we propose that the MVB began at about 16 Ma, when an intermediate to mafic volcanic arc with a rough E-W orientation start to form.

The tectonic evolution of the western and central parts of the MVB is characterized by a middle Miocene phase of transcurrent faulting followed by a transtensional to extensional phase between the late Miocene to the present. Deformation is concentrated within a NW-SE trending zone in the western part and in a 50-70 km wide E-W zone in the central part of the MVB. The coincidence between the onset of the MVB and the middle Miocene phase of transcurrent faulting leads us to propose that the NW-SE and E-W transcurrent faults could have provided preferential crustal magma paths, allowing the formation of the MVB with its oblique orientation with respect to the trench.

KEY WORDS: Geochronology, radiometric ages, stratigraphy, structure, volcanic terrains, Sierra Madre Occidental, Mexican Volcanic Belt, tectonic evolution.

INTRODUCTION

Volcanic rocks of Oligocene and younger ages widely exposed in central Mexico are usually referred to two major volcanic arcs, the Sierra Madre Occidental (SMO) and the Mexican Volcanic Belt (MVB), although the chronological and spatial definition of these arcs remains a matter of controversy. Whereas the age of the SMO volcanics to the north of the MVB is well constrained in the time span Eocene-Early Miocene (Montigny *et al.*, 1987 and reference therein; Demant *et al.*, 1989; Aguirre-Diaz and McDowell, 1991 and reference therein), no agreement exists about the onset of MVB activity, which earlier workers suggested to be either Quaternary (Demant, 1978; 1981), late Pliocene (Cantagrel and Robin, 1979; Robin, 1981), early Pliocene (Nixon *et al.*, 1987) or late Oligocene (Gunn and Mooser, 1971; Mooser, 1972; Negendank, 1973). Pasquarè *et al.* (1988, 1991) postulated the existence of a volcanic sequence of late Miocene age being located in between the two arcs, in the central part of the MVB. These contradictions are partly due to the local extent of some studies and because stratigraphic works and geological mapping are still on a reconnaissance scale in several areas of Mexico. Nevertheless the number of radiometric analyses carried out in the last decade is significant and can provide a first definition of extension in time and space of these volcanic arcs.

The purpose of this paper is to review the current geologic knowledge of the SMO and MVB volcanic arcs in the frame of the tectonic evolution of central Mexico. We analyze the available geochronologic data in order to reconstruct the temporal and spatial distribution of the two arcs. We then integrate the radiometric data with the volcanic stratigraphy. The resulting picture is used to revise the time interval of the tectonic phases recognized in previous studies. Finally, we discuss the relations between the major volcanic events and tectonic phases and we propose a model for the transition from the SMO to the MVB.

VOLCANIC EVOLUTION

2.1 Radiometric data analysis

We have compiled a database of Oligocene to Present radiometric ages of igneous rocks comprised between latitude 16° and 23°N and longitude 96° and 106°E. Part of these data appeared in earlier compilations by Venegas *et al.* (1985), Nixon *et al.* (1987) and Garduño and Gutierrez (1992). We have added ages not published in those papers and ages reported in university theses and internal C.F.E. reports totaling 520 ages. The ages of intrusive rocks represent less than 10% of the total data set. About 95% of the database is composed of K-Ar ages and 93% of the data have experimental errors not exceeding 30% of the age. Age determinations with an error exceeding 50% of the age were discarded.

In analyzing the radiometric ages some care is needed, since they are not necessarily representative of the areal distribution and of the composition of the overall volcanic

products erupted during each time interval. Nevertheless we believe that the database is sufficiently large to draw some conclusions, at least at a regional scale.

The SMO and MVB arcs are usually defined by their orientation and by the overall composition of their products. The SMO volcanic arc is characterized by a rough NNW-SSE orientation and is dominated by chemically differentiated products (Cameron *et al.*, 1987), whereas the MVB has a roughly WNW-ESE to E-W trend and a dominantly basaltic to andesitic composition (Aguilar and Verma, 1987). We analyze the spatial distribution and the composition of dated rocks in order to study the transition between the two arcs.

A first analysis of the database was performed by plotting rock ages versus distance from the present trench for the three main longitudinal sectors defined in Pasquarè *et al.* (1986) (Figure 1). This plot shows that west of longitude 100°W (western and central sectors) the volcanic activity has been continuous since the Oligocene. Between 38 and 26 Ma in all three sectors the volcanism extended over a distance of more than 500 km from the present trench. From 26 to 16 Ma, in the western and central sectors, the arc sharply narrowed and the volcanic front stepped back to about 230 km from the present trench. East of long. 100° W the volcanic activity ceased almost completely. It is interesting to note that the recession of the volcanic front seems to have occurred at younger ages from west to east (about 31 Ma in the western sector, about 28 Ma in the central sector and 26 Ma in the eastern sector). Since 16 Ma the areal distribution of volcanic products appears fairly constant. In the western and central sectors the main axis of the arc is located between 200 and 300 km from the trench, whereas in the eastern sector the main part of the volcanic rocks is emplaced 400-500 km from the trench. A progressive migration of the volcanic front toward the trench is observed in the western sector since 5 Ma and in the eastern sector since 15 Ma. The volcanic front in the central sector also migrated trenchward in the last million years.

The evolution in the composition of the volcanic products is analysed in Figure 2. The distribution of radiometric ages was subdivided according to the petrography of the dated samples. A change in the dominant composition of volcanic rocks took place at about 16 Ma. In the Oligocene and the early Miocene, the composition of the dated rocks is largely silicic whereas since middle Miocene mafic and intermediate products become dominant.

The areal distribution of the volcanism is shown in Figure 3. The location of the dated rocks is illustrated in four significant time intervals. Rocks with ages between 38 and 26 Ma are scattered in a wide NNW-SSE trending belt which appears truncated by the present Acapulco trench. The great abundance of ignimbrites among the dated rocks is probably the cause of the large width of the arc, since these pyroclastic flows can extend as far as 220 km from the vent (Cas and Wright, 1987). Between 26 and 16 Ma

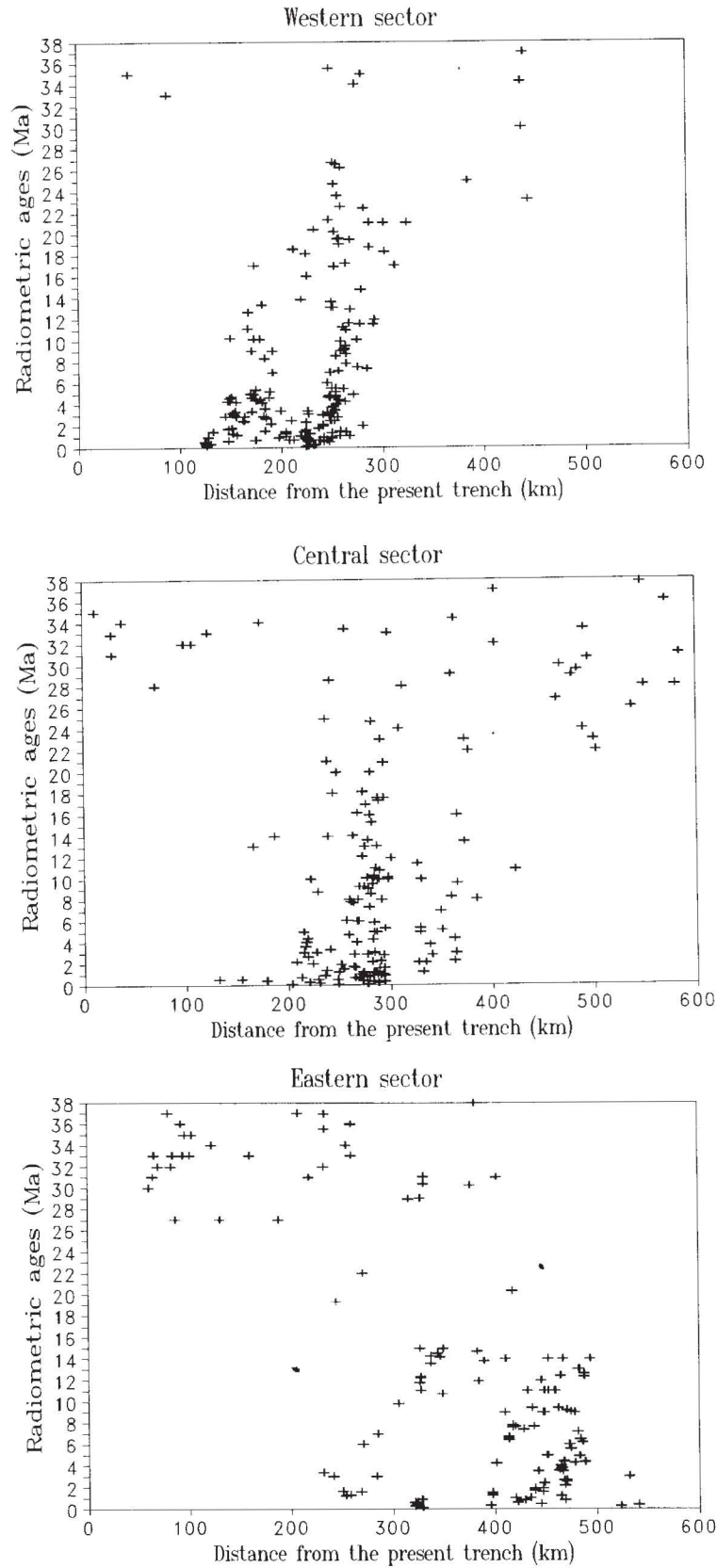


Fig. 1. Radiometric age of igneous rocks in central Mexico vs. distance from the present trench. Geological limits between the three sectors are the Guadalajara triple junction (long. 103°30'W) and the Taxco-Querétaro fault system (approximately long. 100°W)(see chapter 3 for details). The data set is composed of 520 radiometric ages.

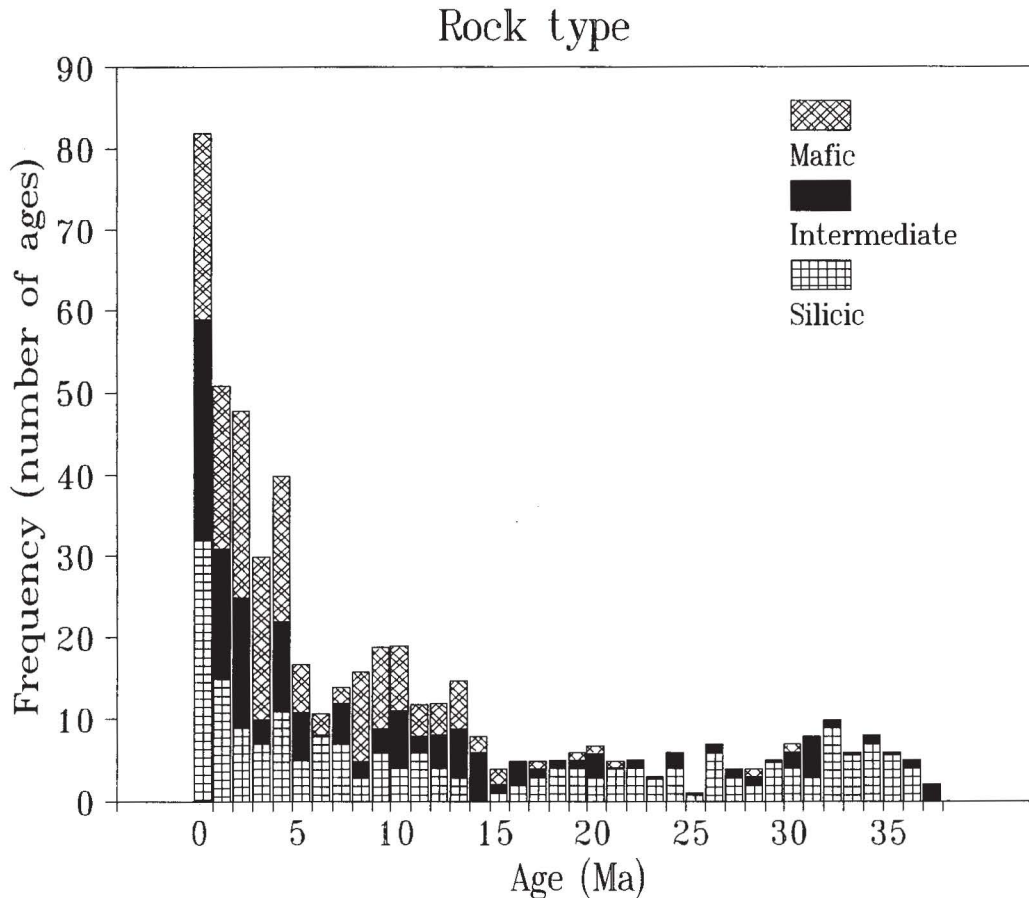


Fig. 2. Histogram of radiometric ages; the bars are subdivided according to the composition of the dated samples. Silicic: rhyolites to dacites; intermediate: andesites and related rocks; mafic: basalts and related rocks.

(latest Oligocene-early Miocene) the volcanism appears limited to the south by a WNW-ESE trending front located between lat. 21°N and 17°N at a distance of over 200 km from the trench. Rocks younger than 16 Ma are evenly distributed along a belt trending WNW-ESE in the western sector and E-W in the central and eastern ones.

2.2 Geologic summary

The sample locations merely approximate the extension of the two volcanic arcs as they are often concentrated in areas of economic or scientific interest, and because of logistic limitations of sampling. Dated samples may define the distribution of volcanic products, but the corresponding volcanic centers may be located quite far away. Moreover, local gaps in the volcanic activity can only be recognized by regional geologic and stratigraphic studies. In order to overcome these limitations we have integrated the geochronologic data with published and unpublished geologic studies to reconstruct the areal distribution of the Oligocene to Present volcanic products (Figure 4). In this section we review the geologic features of these volcanic sequences.

The SMO sequence, exposed in northwestern Mexico, contains 1500-2000 m of sequences that yielded ages with-

in the time intervals 51-40 Ma, 35-27 Ma and 24-20 Ma (Montigny *et al.* 1987 and references therein; Demant *et al.*, 1989; Aguirre-Diaz and McDowell, 1991 and reference therein). The Eocene part of the sequence consist of silicic ash-flow tuff and intermediate lava flows and domes; the younger rocks are voluminous ignimbrites with subordinate amounts of alkalic basalts, especially in the early Miocene. This sequence forms a continuous plateau from the USA border to the latitude of the MVB and is parallel to the Pacific coast of Mexico. The southern part of the SMO volcanic plateau is exposed in the study area between Tepic and Querétaro (Figure 4). Here the sequence is composed of ignimbrites, rhyolitic domes and subordinate andesitic lavas which yield ages between 37 and 18 Ma (Gross, 1975; Gastil *et al.*, 1979; Nieto *et al.* 1981, 1985; Labarthe *et al.*, 1982; Pasquarè *et al.*, 1991). It is uncertain whether the SMO sequence underlies everywhere the MVB, because several wells drilled for geothermal purposes encountered the Mesozoic basement directly below late Miocene or early Pliocene andesites (Venegas *et al.*, 1985). Andesitic lavas with ages ranging from 31 to 29 Ma have been encountered only in wells of the Mexico City area (Mooser *et al.*, 1974; Pérez-Cruz, 1988).

South of the present MVB a volcanic activity coeval with the SMO is reported only east of long. 103°. In the

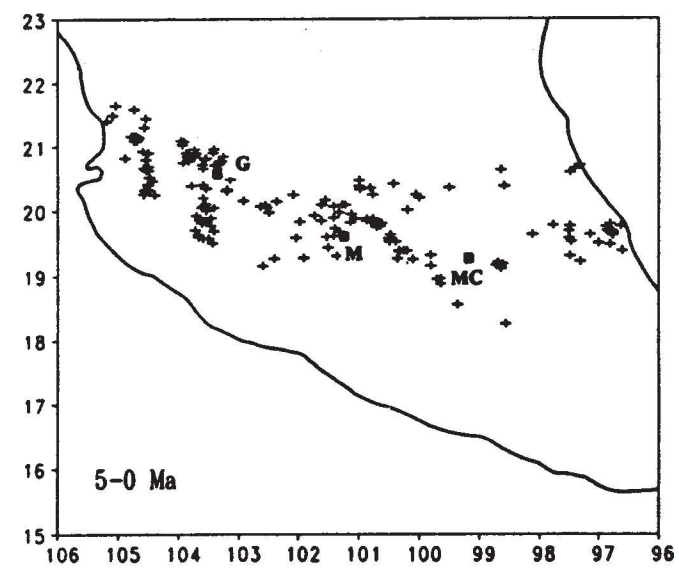
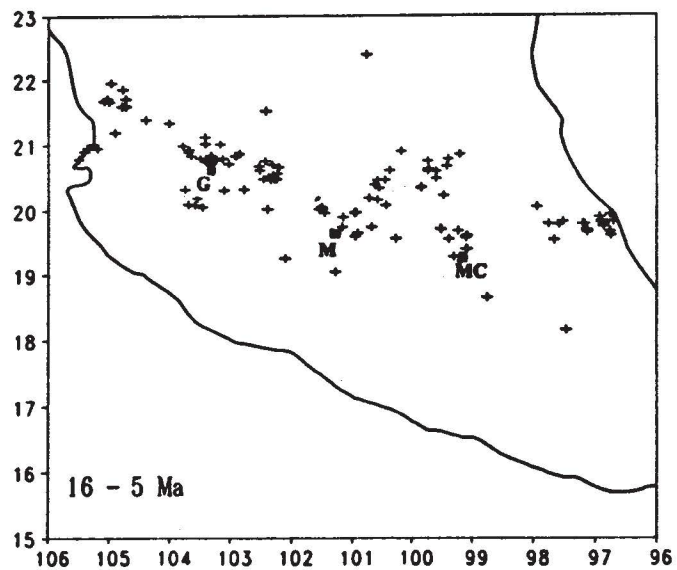
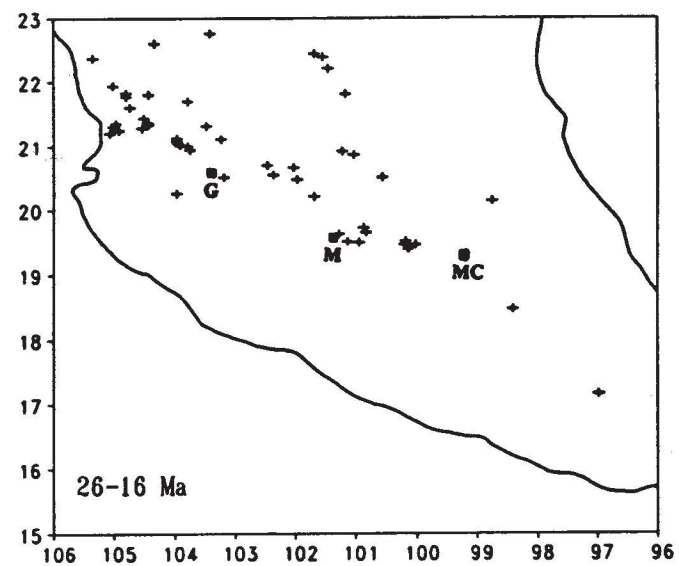
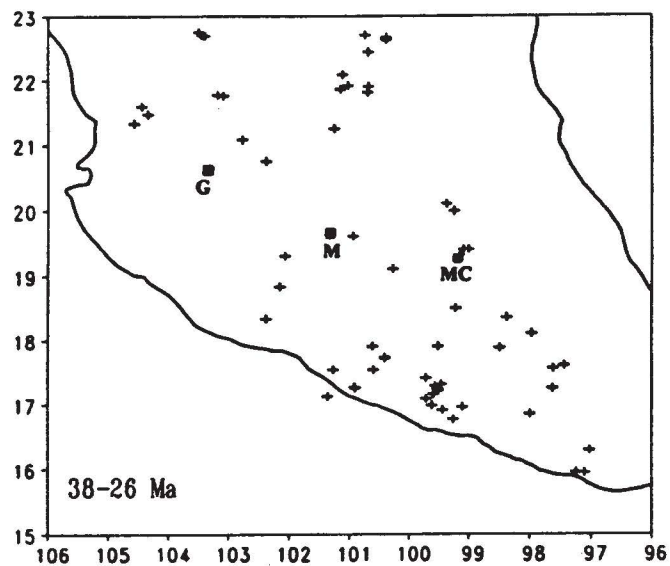


Fig. 3. Areal distribution of igneous rocks for the periods 38-26 Ma, 26-16 Ma, 16-5 Ma and 5-0 Ma. Present-day coast lines for reference. G=Guadalajara, M=Morelia, MC=Mexico City.

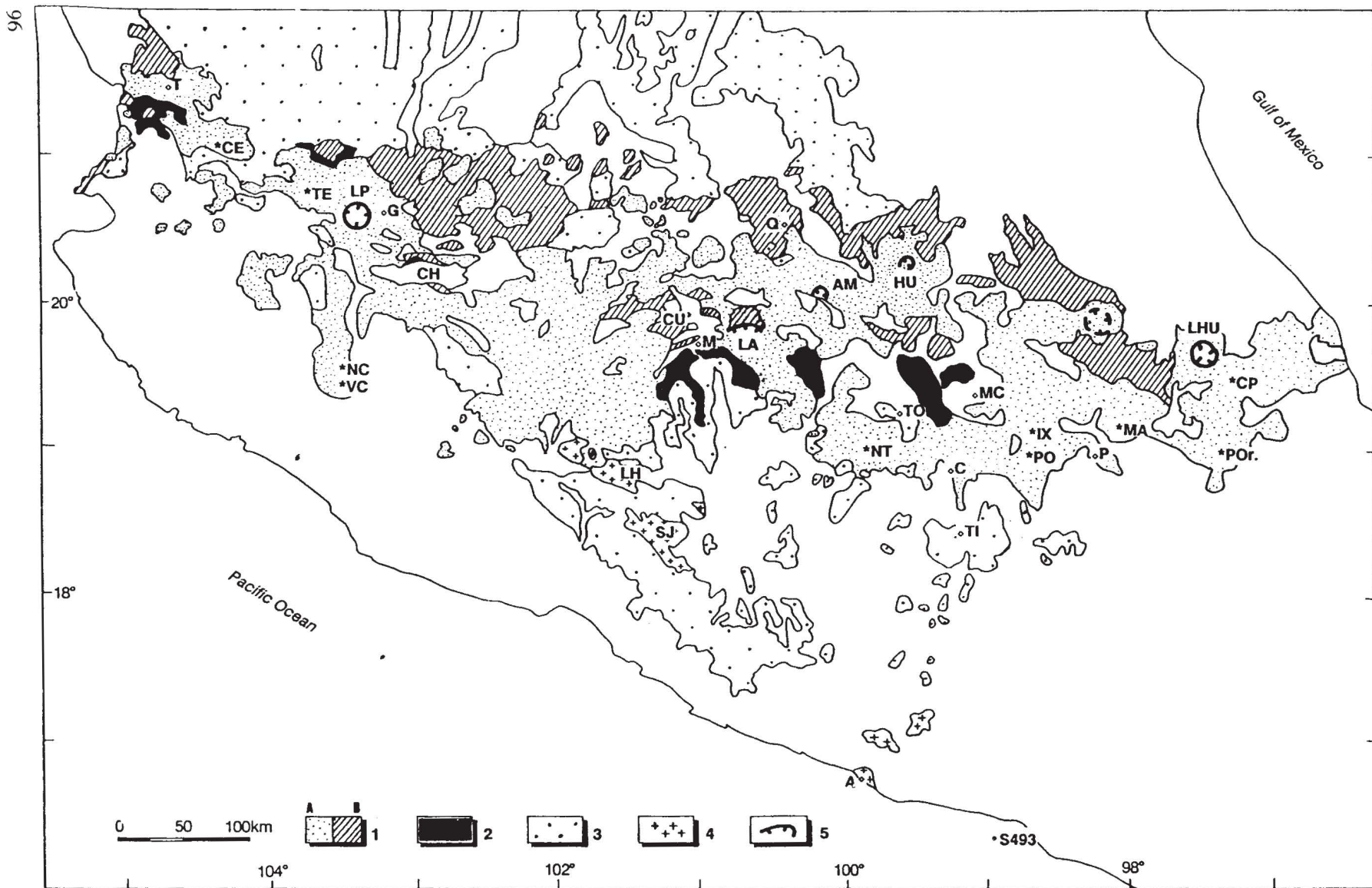


Fig. 4. Geologic sketch-map of Oligocene to Present volcanic terrains of central Mexico (compiled from sources cited in the text and our unpublished reconnaissance works). 1 = a) Plio-Quaternary, b) late Miocene; 2 = middle Miocene. 3 = Oligocene to early Miocene, 4 = Main calcalkaline plutonic bodies of Oligocene age. 5 = main MVB calderas. LP = La Primavera; LA = Los Azufres; AM = Amealco; HU = Huichapán; LHU = Los Humeros. T = Tepic; G = Guadalajara; M = Morelia; Q = Querétaro; TO = Toluca; MC = Mexico City; C = Cuernavaca; P = Puebla; TI = Tilzapotla; A = Acapulco; LH = La Huacana; SJ = San Jerónimo; CH = Chapala lake; CU = Cuitzeo. Stars indicate the main MVB stratovolcanoes: CE = Ceboruco; TE = Volcán Tequila; NC and VC = Nevado and Volcán Colima; NT = Nevado de Toluca; IX = Ixtaccíhuatl; PO = Popocatepetl; MA = Malinche; CP = Cofre de Perote; PO_r = Pico de Orizaba.

Sierra Madre del Sur, north of Zihuatanejo, Kratzeisen *et al.* (1991) found a composite sequence of andesitic to dacitic lava flows and intermediate to felsic ignimbrites with ages from 46 to 30 Ma. The complex is intruded by at least three families of dikes, mostly of Oligocene age. A similar volcanic succession is exposed in the Mil Cumbres area, south of Morelia, where the dated rocks range from 33 to 18 Ma in age (Pasquarè *et al.*, 1991). Further to the east, along the Mexico City - Acapulco section, Campa *et al.* (1981) describe dacitic to rhyolitic lava sequences with ignimbrites dated 34.5 Ma at Tiltzapotla (DeCserna and Fries, 1981; Figure 4). In all these areas the Oligocene volcanics are generally more eroded than in the SMO but their thickness is often comparable. The dissection of this region has exposed a chain of calcalkaline plutonic bodies of Oligocene age (Figure 4) which likely represent the roots of the volcanic centers (Clark *et al.*, 1982; Pantoja-Alor 1983; Böhnelt *et al.* 1988; Kratzeisen *et al.*, 1991; Herrmann *et al.*, 1993). On the southeastward prolongation of this plutonic chain, about 80 Km ESE of Acapulco, a dioritic basement with an age of 34.5 Ma was encountered at site 493 of Leg 66 of the Deep Sea Drilling Project (Bellon *et al.* 1983). In some cases the above data may be considered as minimum ages, but they prove also the existence of a thermal event related to Oligocene volcanic activity in the Sierra Madre del Sur.

In summary, the available data indicate that during the Eocene and the Oligocene a volcanic arc representing the prolongation of the SMO extended as far south as the present Acapulco trench. South of latitude 20° the volcanism seems less differentiated than in the better studied areas of northwestern Mexico. In the north-western part of the study area (Nayarit and Jalisco States) and south of Morelia this volcanism lasted until early Miocene and define a WNW-ESE trending arc.

During middle Miocene, volcanism occurred in scattered areas along a belt crossing Central Mexico in an E-W direction. Volcanic sequences of middle Miocene age are reported northwest of Guadalajara (Nieto *et al.*, 1985) and, more to the east, along the southern part of the present MVB. Andesitic to dacitic volcanic successions with radiometric ages ranging between 16 and 11 Ma are exposed between Morelia and Mexico City in the Sierra de Mil Cumbres, Sierra de Angangueo, Sierra de las Cruces and Sierra de Guadalupe regions (Mooser *et al.*, 1974; Negendank *et al.*, 1981; Pasquarè *et al.*, 1991).

In late Miocene time the volcanic activity was characterized by a widespread and uniform basic volcanism. Large basaltic plateaus formed an E-W elongated belt located to the north of the present volcanic arc (Ferrari *et al.*, this issue, a). The radiometric age of these rocks decrease towards the east: about 13 to 10 Ma along the Pacific coast (Gastil *et al.*, 1979), 10.5 to 7 Ma in the Guadalajara-Arandas area (Watkins *et al.*, 1971; Nieto *et al.*, 1981; Moore and Carmichael, 1991; Spinnler *et al.*, in press) and 8.1 to 6.5 in the Querétaro-Pathé area (Pasquarè *et al.*, 1991; Nichols, 1970; Suter *et al.*, 1992a). Between Guadalajara and Querétaro these basalts are clearly separated

from the SMO ignimbrites by erosional deposits, whereas more to the south, around the Chapala and Cuitzeo lakes, they over andesitic sequences of middle to late Miocene age (Ferrari *et al.*, this issue, a). Ignimbrites and acidic dome complexes are locally associated with the basalts in the Guadalajara, Los Azufres and Huichapan areas (Gilbert *et al.* 1985; Ferrari *et al.*, 1991; Milàn and Herrera, 1987).

The early Pliocene seems to be characterized by a limited distribution of volcanic products and by the occurrence of differentiated rocks. Mafic products, which include also alkaline varieties, are mainly exposed in the western part of the MVB (Gilbert *et al.*, 1985; Nieto *et al.*, 1985; Allan, 1986; Richter and Carmichael, 1992), or at its easternmost end (Negendank *et al.*, 1987; López-Infanzón, 1990). By contrast, rhyolitic domes of this age are reported in the Tepic area (Gastil *et al.* 1979), NW of Guadalajara (Gilbert *et al.* 1985) and to the north and south of Los Azufres caldera (Ferrari *et al.*, 1991). In addition various ignimbritic units were emplaced in this period in the Guadalajara area (Nieto *et al.* 1985; Gilbert *et al.* 1985) and in relation with the Huichapan, Amealco and Los Azufres calderas (Aguirre-Díaz, 1990; Verma *et al.*, 1991; Soler-Arechalde *et al.*, 1993; Ferrari *et al.*, 1991; Ferrari *et al.*, 1993). Since late Pliocene, basaltic and andesitic products again became dominant. In the western and eastern sectors of the present volcanic arc large andesitic to dacitic stratovolcanoes are dominant, whereas the central sector is characterized by fields of cinder and lava cones (Bloomfield, 1973; Hasenaka and Carmichael 1985). Volcanism generally shows a southward migration with time (Nixon *et al.* 1987; Hasenaka and Carmichael 1985; Ban *et al.*, 1992). Subordinate alkaline products are erupted mainly in the western and eastern sectors (Negendank *et al.* 1987; Luhr *et al.*, 1989; Verma *et al.*, 1989), and often in spatial and chronological vicinity with the calcalkaline ones.

2.3 Definition of the SMO and the MVB

Let us attempt to define the time boundary between the SMO and the MVB arcs.

During Oligocene the SMO volcanic arc formed a wide, NNW trending belt which is interrupted by the present Acapulco trench and extended to the east up to the Latitude of Mexico City. The volcanic products were dominantly silicic, although south of the MVB intermediate rocks are also widespread. In latest Oligocene, volcanism ceased south of the present MVB, while towards the east it reached the same extent as before (Figure 1, 3 and 4). Between 22 and 16 Ma the volcanic activity waned north of the present MVB and was limited to a 100-km-wide belt with a WNW-ESE orientation, whose front was parallel to the present trench at a distance of about 230 km (Figure 1 and 3). This geometry could indicate that the early Miocene arc was already related to a subduction zone similar to the present one, nevertheless, the volcanic products emplaced in this period are mostly ignimbrites and rhyolites and, at least in the northern part of the study area, are clearly separated from the younger ones by erosional deposits or unconformities. In this time period the arc was

not developed yet in the eastern sector of the study area (Figure 1 and 3). For these reasons we regard the early Miocene volcanism as the last activity of the SMO.

Since 16 Ma, the distribution of volcanic products defines an arc which maintains a WNW-ESE orientation in its western part and an E-W trend in the central and eastern parts. In this period the volcanic activity becomes dominantly mafic to intermediate (Figure 3) while in late Miocene times it acquires a uniform character and a widespread distribution. Based on the widely acknowledged features of the MVB, its obliquity with respect to the trench and the mafic to intermediate character of its products, we propose that the MVB began at approximately 16 Ma. On a local scale the boundary between the two arcs (a gap in the volcanism) is clearly observable in the northern part of the central and eastern sectors (north of Chapala and Cuitzeo lakes and in the Querétaro area, Figure 4). In the remaining areas the transition from the SMO to the MVB is defined by a rather gradual change in the general orientation of the arc and in the dominant composition of the products.

STRUCTURAL EVOLUTION

3.1 Introduction

Structurally, central Mexico can be divided into three major provinces: (1) The SMO plateau north of the present MVB, which is mainly affected by NNW-SSE to NNE-SSW trending grabens; (2) the MVB, which is marked by a fault zone with a dominant E-W orientation; (3) the Sierra Madre del Sur, located south of the present MVB and dominated by WNW-ESE trending faults. According to the general distribution of the fault systems the MVB was subdivided by Pasquarè *et al.* (1986) into three sectors: (1) a western sector comprising the Tepic-Chapala and Colima grabens (Figure 5); (2) a central sector extending from Guadalajara to the Querétaro-Taxco fault system; (3) an eastern sector extending from the Querétaro-Taxco fault system to the coast of the Gulf of Mexico.

In this section we review the structural data available for these major provinces of central Mexico, with special attention on the MVB.

3.1 Sierra Madre Occidental and Sierra Madre del Sur

Structural studies of these two provinces are scarce. The SMO has been involved in several E-W extensional phases since 30 Ma, which have been considered to be the southern prolongation of Basin and Range tectonics (Henry and Aranda, 1992). The normal faulting causing major NNW-SSE to NNE-SSW trending grabens started at the beginning of Miocene and was subsequently reactivated around 12 Ma (Henry and Aranda, 1992). The Sierra Madre del Sur has been affected by a left-lateral strike-slip regime which mostly produced transtensional structures during the eastward migration of the Chortis Block and the formation of the Caribbean (Ratschbacher *et al.*, 1991; Kratzeisen *et al.*, 1991). Although these tectonic events

could have started in late Cretaceous times (Ratschbacher *et al.*, 1991), the main transtensional deformation seems to have occurred since the Eocene (Robinson *et al.*, 1990) and was probably coeval with the Oligocene volcanism of the Sierra Madre del Sur.

3.2 The MVB

The structure of the MVB developed through several tectonic phases. Here we focus more in detail on these phases and we describe the geometry, kinematics and age of the major fault systems. The structure of the MVB was studied between the Pacific coast and the longitude of Querétaro; more to the east, our interpretation is based on a reconnaissance remote-sensing study. The ages of fault motions were revised according to the data discussed in the previous section. Inversion of fault slip data helped reconstruct the shape and orientation of the paleo-stress tensors; it is based on the calculation of the best-fitting mean deviatoric stress tensor according to the methods in Carey (1979) and Reches (1987). Most of the results were published in Pasquarè *et al.* (1988), Tibaldi (1989), Ferrari *et al.* (1990), Garduño and Tibaldi (1991). We present a synthesis in the form of the stress tensors with the best reliability (see Carey, 1979), plus some new results. Additionally, we include (for the late Quaternary stress field) results of borehole elongations and earthquake focal plane solutions related to the MVB stress province (Suter, 1991). In the following we describe the tectonic evolution of the various sectors of the MVB from west to east.

3.2.1 Western sector

The western part of the MVB is dominated by three extensional fault systems of broadly N-S, E-W and NW-SE orientation, called Colima, Chapala, and Tepic-Zacoalco rifts by Luhr *et al.* (1985). Their intersection some 50 km south-southwest of Guadalajara is considered as an active triple junction by Luhr *et al.* (1985) and Allan *et al.* (1991). The Tepic-Zacoalco rift is characterized by WNW, NNW, and NE striking faults, in order of abundance. WNW fault planes show sometimes superposition of three families of striations. The older two families are of strike-slip type, with left-lateral motions followed by right-lateral motions, whereas the latest movement is dip-slip extension (Garduño and Tibaldi, 1991; Michaud *et al.*, 1991). Closer to the triple junction, normal motions seem to be more limited on these planes, and usually took place on the NNW striking faults (Garduño and Tibaldi, 1991). The greatest (σ_1) and least (σ_3) principal stresses are horizontal and oriented NW-SE and NE-SW respectively during the oldest phase, and switch directions in the subsequent right-lateral phase. Dip-slip extension along NNW striking planes was induced by a perpendicular and horizontal σ_3 , while σ_1 was vertical. NE faults are mainly developed south of Tepic along the Pacific coast (Puerto Vallarta graben) and in the Ceboruco area (Ferrari *et al.*, this issue b). Concerning the timing of these events, the strike-slip phases can both be referred to the middle Miocene (Michaud *et al.*, 1991) whereas the extensional basins developed since late Miocene (Gastil, 1979; Quintero and

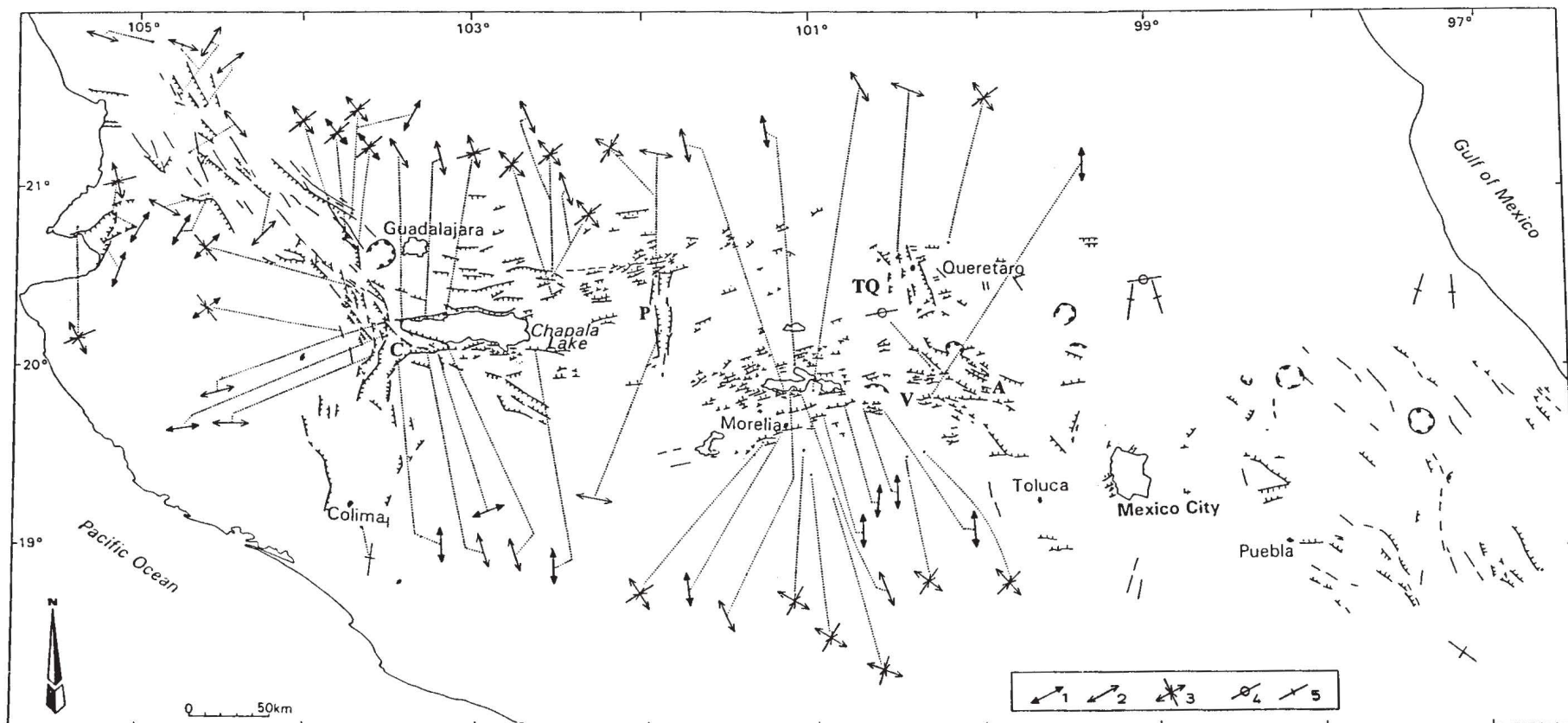


Fig. 5. Main Neogene-Quaternary structures of the Mexican Volcanic Belt with selected stress orientation measurements. Lines with ticks represent normal faults or oblique normal faults; simple lines are faults based on remote sensing interpretation. 1=Quaternary direction of σ_3 ; 2=late Miocene or Pliocene direction of σ_3 ; 3=middle Miocene direction of σ_3 (diverging arrow) and σ_1 (converging arrow); 4=direction of $\sigma_{H_{max}}$ from focal mechanism; 5=direction of $\sigma_{H_{max}}$ from borehole elongation measurements (Suter, 1991). C=Citala graben; P=Penjamillo graben; V=Venta de Bravo fault; A=Acambay graben; TQ=Taxco-Queretaro faults.

Guerrero, 1992; Ferrari *et al.*, this issue, b) and are probably still active near the triple junction.

The Colima graben is characterized by N-S striking normal faults in the southern larger segment, and by NNE to N-S normal faults in the northern segment (Figure 5). Striations on pre-Quaternary fault planes show pure normal motion produced by an E-W trending σ_3 (Barrier *et al.*, 1990). The same stress direction acted during the Quaternary. The opening processes are reported to have begun approximately 5 Ma ago (Allan, 1986, Allan *et al.*, 1991) but it is uncertain if extension has been taking place south of Colima volcano during Tertiary and Quaternary times (Serpa *et al.*, 1992).

3.2.2 Central sector

Between Guadalajara and Mexico City the structure of the MVB is dominated by E-W to ENE striking left-lateral normal faults which mainly developed between the end of the middle Miocene and the Quaternary (Figure 5). These faults occur in three areas. The first fault zone, known as the Chapala rift, is located north of latitude 20° in the region of Chapala lake. The second is developed to the southeast around Cuitzeo lake and Morelia, and is named here Morelia fault zone. Between Toluca and Puebla a third, less deformed zone is affected by E-W to NE-SW faults (Figure 5). These three fault sets are linked by major N-S to NNW-SSE fault structures which were active as extensional systems in Plio-Quaternary times, and which locally reactivate older faults. They are the Penjamillo graben in the west, and the Querétaro fault system in the east. East of Puebla, the main faults strike NW and N-S (Figure 5).

3.2.2.1 The Chapala rift

The Chapala rift represents the E-W arm of a triple junction. The rift developed mainly during late Miocene and Pliocene (Delgado, 1992). During the Quaternary it migrated southward to the latitude of the Citala graben (Garduño and Tibaldi, 1991). Stress tensor determinations give a NNW-SSE trending and horizontal σ_3 during Pliocene time at the eastern tip of the Chapala depression and during the Quaternary at the eastern tip of the Citala depression (Figure 5). The E-W to ENE faults show sometimes a superposition of two families of striations; the oldest was produced by left-lateral motions while the more recent one developed by pure normal motions (Garduño *et al.*, in press). In some scattered outcrops, an intermediate phase of left-lateral normal motion is observed.

The horizontal striations were produced by a stress field with a NE-SW trending and horizontal σ_1 and NW-SE oriented and horizontal σ_3 , whereas the oblique motions were caused by a NW-SE to NNW-SSE trending σ_3 , followed by a clockwise rotation of σ_3 up to N-S and NNW-SSE orientations. Time relationships between the left-lateral transcurrent and left-lateral normal motions are not clear. It is well established that pure normal motions occurred after the left-lateral normal motions. A major late

Quaternary E-W striking normal fault SE of Chapala Lake (Pajacuaran fault) requires a N-S and horizontal direction of σ_3 .

3.2.2.2 Penjamillo graben

This graben is bounded by N-S trending faults which are mostly developed along its western side, where an extensional stepover is occupied by old lacustrine deposits. The most centrally located graben faults dislocate ignimbritic rocks of the Sierra Madre Occidental and lava flows belonging to two generations of volcanoes dated as Pliocene-early Quaternary on the basis of their morphology (Tibaldi, 1990). The ignimbrites of early Miocene age are also cut by N-S right-lateral strike-slip faults. These faults were partially reactivated as right-lateral normal or pure normal faults during the opening of the Penjamillo graben. At the northern and southern end of the graben, the N-S faults intersect with the ENE fault swarms of the Chapala and Morelia sectors. Crosscutting relationships, mainly observed on aerial photographs, indicate mutual dislocations which suggest contemporaneous movements along both fault systems.

The computed stress tensors are characterized by a horizontal and NNE-SSW oriented σ_1 and a horizontal and WNW-ESE trending σ_3 for the older transcurrent phase, and by a horizontal and WNW-ESE oriented σ_3 and a vertical σ_1 orientation for the opening phase.

3.2.2.3 The Morelia zone

The tectonic history of the Morelia zone resembles that of the Chapala rift. E-W to ENE major faults dominate as a result of a complicated tectonic evolution. The oldest fault motions were of left-lateral transcurrent type, followed by normal left-lateral and, subsequently, by normal motions (Pasquarè *et al.*, 1988, 1991). Strike-slip striations were produced by horizontal NE-SW σ_1 and NW-SE σ_3 . Oblique motions were caused by a NW-SE to NNW-SSE σ_3 , followed by a clockwise rotation of σ_3 into a N-S orientation. The transcurrent phase is post-early Miocene in age. It was followed by the opening of the main depressions accompanied by left-lateral normal motions. The extensional movement is still active in the eastern part of the sector (Sußer *et al.*, 1992b), as indicated by geologic and morphotectonic indicators along the Venta de Bravo fault and the Acambay graben (about 120 km east of Morelia, Figure 5), and by the seismicity. An earthquake focal mechanism solution (Astiz, 1980, 1986) and Holocene striations indicate that normal motions with a minor left-lateral component are still active. E-W normal faulting is also observed 100 km east of Querétaro, in the Aljibes half-graben, (Suter *et al.*, 1992a)

3.2.2.4 The Querétaro fault system

The Querétaro depression is limited by NNW striking master faults which locally intersect minor E-W to ENE faults (Figure 5). Scattered NNW trending faults are also observed together with NW faults more to the south, at

least up to the latitude of Toluca. Pasquarè *et al.* (1986 and 1991) propose the Querétaro-Taxco alignment as a major structural boundary, mostly reactivated during Pliocene times, between the central and eastern segments of the MVB. Actually NW, ENE and NE faults can be found up to the longitude of Mexico City. From this point of view, the zone between Toluca and Mexico City can be considered as an area of gradual transition to the eastern sector where NW faults are dominant. Striations on NNW normal faults near Querétaro indicate a ESE-WNW horizontal σ_3 and a vertical σ_1 . In older rocks, N-S to NNE right-lateral strike-slip and NE to E-W left-lateral strike-slip faults could be observed. They yield a horizontal NE-SW σ_1 and NW-SE σ_3 . The faults of the Querétaro system cut rocks dated at 8.1 Ma (Pasquarè *et al.*, 1991).

3.2.3 Eastern sector

This area, located between Mexico City and the Gulf of Mexico, is characterized by NW to NNW striking faults and volcanic lineaments. The only variation to this trend is represented by the Pico de Orizaba-Cofre de Perote N-S volcanic lineament, located 100 km east of Puebla (Figure 5). Fault slip measurements are not reported for this area. Photogeological observations suggest post-Miocene normal fault motion around Puebla. Stress orientations provided by borehole elongations indicate a NNW to NNE orientation of the horizontal greatest principal stress along the northern limit of the MVB, whereas volcanic alignments indicate that the eastern part of the MVB is characterized by E-W to NE-SW horizontal greatest principal stress (Suter, 1991).

DISCUSSION AND CONCLUSIONS

The transition from the SMO to the MVB may have occurred in the period 26-16 Ma (see section 2). In our view, the arc reorientation which took place at this time reflects the progressive opening of the new Acapulco trench. Reconstruction of paleo-plate motion (e.g. in Pindell *et al.*, 1988) and geological studies (Robinson *et al.*, 1990; Ratschbacher *et al.*, 1991; Kratzeisen *et al.*, 1991) indicate that the Acapulco trench developed at the former transform boundary between the North America plate and the Chortis block (nuclear Central America). The latter began to move east-southeastward from a location near the coast of Michoacán in the Eocene (Pindell *et al.*, 1988; Robinson *et al.*, 1990) producing left-lateral transtensional deformations in a widespread area of Sierra Madre del Sur (Ratschbacher *et al.*, 1991; Kratzeisen *et al.*, 1991). Karig *et al.* (1978) discovered that the accretionary complex at the trench off Oaxaca began to form in the late Miocene. Based on this data we may hypothesize that, in the study area, the present Acapulco trench formed progressively from west to east between Eocene and middle Miocene. The continental volcanism appears to match this process with a delay of some millions of years, required for the slab to reach the suitable depth for melt generation. Thus, although the 3D geometry of the subduction zone could also be important in defining the location of the arc, we believe that the migration of the trench was ultimately responsible for the observed arc migration.

At the other side of the MVB the gradual waning of the SMO arc north of Lat. 21°N followed the progressive inactivation of the former trench in early to middle Miocene times, as the East Pacific Rise progressively collided with the North America plate and Baja California started to move north-northwestward (Mammerickx and Klitgord, 1982; Stock and Hodges, 1989).

In the MVB we find a phase of transcurrent faulting, followed by transtensional faulting and eventually by extension. Absolute timing of these deformation phases is still somewhat uncertain. We suggest that the transcurrent motions developed during the middle Miocene but further investigation is needed to verify if this strike-slip motion was already active during the early Miocene or if it persisted locally in some areas. In the western and central part of MVB, extensional basins have developed since the late Miocene and the formation of some of these basins is probably related to the transtensional deformation phase.

If we compare the tectonic and volcanic evolution in the study area we find that the onset of the MVB coincides with the development of middle Miocene transcurrent faults, which probably provided preferential crustal magma paths as in other volcanic arcs (Tibaldi, 1992). The inception of the late Miocene basaltic volcanism corresponds with the beginning of the extensional deformation phase. We believe that the middle Miocene transition from the SMO to the MVB and the transcurrent phase of deformation occurred at the same time, which could indicate a control of a continental strike-slip fault swarm on the areal distribution of volcanism. Transtensional and extensional faulting guided the emplacement of the late Miocene basaltic plateaux and the rest of Plio-Quaternary volcanism.

In conclusion, whereas the formation of the MVB at a continental scale was probably determined by the migration of the subduction system, which determined the location of the melting zone at depth, at a regional scale the oblique orientation of the MVB with respect to the trench could be due to the orientation of the crustal fault zones that provided suitable magma paths from the source region to the surface.

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- Luca Ferrari^{1,3}, Victor Hugo Garduño², Giorgio Pasquarè¹ and Alessandro Tibaldi¹
- ¹ Dipartimento di Scienze della Terra, Università di Milano, Via Mangiagalli 34, 20133, Milano, Italia
- ² Departamento de Geología, Universidad Michoacana San Nicolás de Hidalgo, Cd. Universitaria, Morelia, Mich., México
- ³Also at: Departamento de Exploración, Gerencia Proyectos Geotermoeléctricos, Comisión Federal de Electricidad, Calle A. Volta 655, Morelia, Mich., México