A widespread mafic volcanic unit at the base of the Mexican Volcanic Belt between Guadalajara and Querétaro

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RESUMEN:
Grandes mesetas basálticas, emplazadas principalmente entre 10 y 6 Ma, forman la parte basal de las vulcanitas de la Faja Volcánica Mexicana (FVM), en el centro de México. En las áreas de Guadalajara y Querétaro, estas mesetas están separadas de las ignimbritas y andesitas de la Sierra Madre Occidental, de edad Oligoceno Tardío a Mioceno Temprano, por un período de calma volcánica marcado por varios depósitos erosionales, mientras que en las áreas alrededor de los lagos de Chapala y de Cuitzeo sobreyacen a secuencias andesíticas de edad Mioceno Medio a Mioceno Tardío. Las lavas de estas mesetas son relativamente primitivas (Mg#66-52), no sufrieron un fraccionamiento de baja presión significativo, y muestran claramente afinidades calci-alcalinas. Estas mesetas de basalto representan el primer evento volcánico en la historia de la FVM amplia y uniformemente distribuído. Los datos geológicos y geoquímicos sugieren que estos basaltos fueron emplazados durante la primera fase tectónica extensional que acompañó a la FVM.

PALABRAS CLAVE: Mesetas de basalto, Mioceno Tardío, elementos mayores, elementos traza, geoquímica, Guadalajara, Querétaro, Faja Volcánica Trans-Mexicana.

ABSTRACT
In central Mexico, large basaltic plateaux, mainly emplaced between 10 and 6 Ma, form the basal part of the Plio-Quaternary volcanics of the Mexican Volcanic Belt (MVB). In the Guadalajara and Querétaro areas these plateaux are separated from the late-Oligocene to early-Miocene Sierra Madre Occidental ignimbrites and andesites by a period of volcanic quiescence marked by various erosional deposits, whereas in the areas surrounding the Chapala and Cuitzeo lakes they overlie andesitic sequences of middle-to late-Miocene age. The plateau lavas are relatively primitive (Mg# 66-52), did not undergo significant low pressure fractionation, and display clear calc-alkaline affinities. They represent the first widespread and uniform volcanic event in MVB history. Geological and geochemical data suggest that these basalts were emplaced during the first extensional tectonic phase that accompanied the development of the MVB.

KEY WORDS: Basaltic plateaux, late Miocene, major and trace elements, geochemistry, Guadalajara, Querétaro, Mexican Volcanic Belt

INTRODUCTION

Geological and geochemical studies of Mexican volcanism have largely focussed on the Oligocene to early Miocene ignimbrites of the Sierra Madre Occidental (SMO) and on the Plio-Quaternary volcanic sequences of the Mexican Volcanic Belt (MVB) (Figure1), although significant volcanic activity also took place during middle- and late-Miocene (Ferrari *et al.*, this issue). A complete Oligocene-to-Quaternary volcanic record is exposed in the region between the Pacific coast and Mexico City, where the MVB overlaps the SMO volcanic arc (Figure 1). In this region Miocene volcanism is mostly represented by andesitic to dacitic sequences located in the southern part of the MVB and by late-Miocene basaltic sequences cropping out in its northern part. The most outstanding geologic manifestations of the late-Miocene volcanism are vast and uniform mafic plateaux largely exposed in the Tepic, Guadalajara and Querétaro areas (Figure 1). These mafic plateaux have been studied only locally (Watkins *et al.*, 1971; Urrutia and Pal, 1977; Verma *et al.*, 1985) or have been considered in the framework of more general geologic investigations (Gastil *et al.*, 1979; Demant, 1981; Nieto *et al.*, 1981; Nixon *et al.*, 1987; Spinnler *et al.*, in press).

In this work we approach the study of this mafic volcanism from a regional perspective in order to understand if it represents a separate event, intermediate between the SMO and the MVB, or whether it is part of the volcanic cycle of the MVB. We present a preliminary geological and geochemical study of the mafic plateaux of the Guadalajara and Querétaro areas, which represent the largest part of the late-Miocene mafic volcanism of central Mexico. Investigations of similar volcanic sequences in the Tepic area are in progress. The results of our study favour the hypothesis that late-Miocene mafic volcanism represents an important event that marks the onset of MVB volcanism.

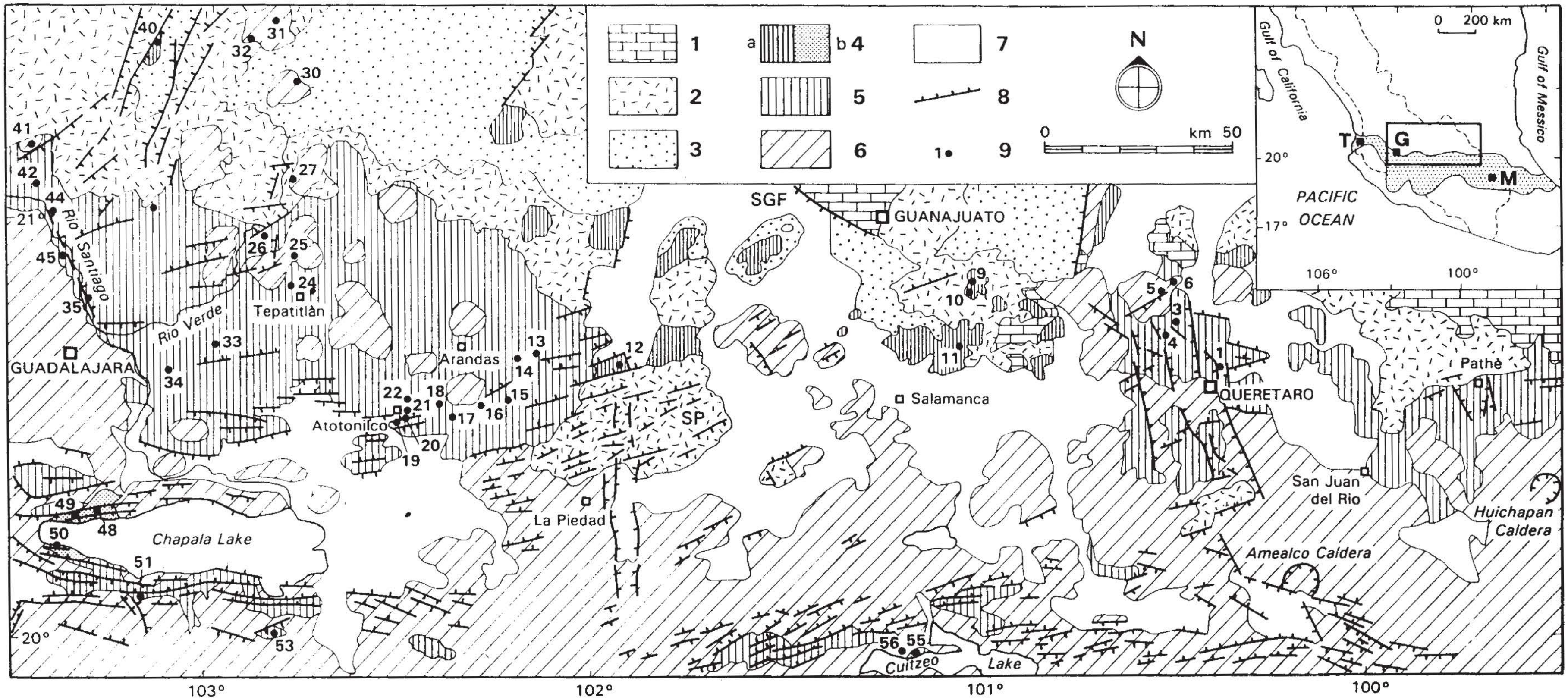

Fig. 1. Geologic sketchmap of the study area (mainly based on Pasquarè *et al.*, 1991; Garduño *et al.*, in press; Spinnler *et al.*, in press). 1 = Mesozoic basement terranes; 2 = Oligocene to early Miocene ignimbrites, rhyolites and andesites of the Sierra Madre Occidental (SMO); 3 = Xoconostle conglomerate and related fluvio-lacustrine sequences; 4 = a) andesitic and basaltic mesas of the area south of Guanajuato, b) Pre-plateau andesites and breccias of the Chapala area; 5 = Late Miocene mafic plateaux of the Río Santiago mafic sequence (RSMS) and Querétaro mafic sequence (QMS); 6 = Plio-Quaternary volcanics; 7 = Quaternary alluvial deposits; 8 = normal faults; 9 = Analyzed samples (numbered as in Table 2, 3 and 4). Inset map shows the location of the study area. Dashed line limits the SMO; dotted area indicates the Plio-Quaternary MVB. T = Tepic; G = Guadalajara; M=Mexico City.

GEOLOGIC SETTING

The investigated region lies between Long. 103° 30' and 99° 30' and Lat. 19° 55' and 21° 30' (Figure 1). It includes the northern half of the MVB, between the Guadalajara triple junction (Luhr *et al.*, 1985) and the NNW-trending Taxco-Querétaro fault system (Pasquarè *et al.*, 1986). Late-Miocene volcanic rocks are exposed mainly in the Guadalajara-Arandas area and in the Querétaro-San Juan del Río area (Figure 1). Because of their different geologic settings we describe these two areas separately. Radiometric dates relevant for our discussion are listed in Table 1.

GUADALAJARA-ARANDAS AREA

West of Longitude 102° the late-Miocene volcanics form a 130 km long, 60 km wide, subhorizontal plateau with a mean elevation of 1900 m a.s.l. The late-Miocene sequence is well exposed along the Rio Grande de Santiago canyon, north of Guadalajara (Figure 1) and is referred to as the Rio Santiago mafic sequence (RSMS).

The RSMS consists of a monotonous sequence of basaltic lava flows with local intercalations of alluvial and lacustrine deposits. Individual flows range between 2 and 10 m in thickness. A typical red soil, several meters thick, covers the surface of the plateau lavas, which are commonly altered to a gray-yellowish colour. Small lava cones cover the RSMS and, north of Lat. 21°N, rest directly above the SMO units. No radiometric dates are available for these centres; we tentatively consider them as post-RSMS because of their relatively fresh morphologies, but we included them in the study for comparison.

North of Guadalajara, along the Río Grande de Santiago canyon, the RSMS is at least 250 m thick (Figure 2a). Its base is formed by basaltic flows, dated 10.2 Ma, overlain by an ignimbritic unit of 10.0 Ma (samples 8 and 11 in Table 1). The upper part of the plateau cropping out east of the Río Santiago yielded ages of 8.0 Ma and 7.3 Ma (sample 23 and 25 in Table 1). A K-Ar date of 8.5 Ma has been obtained for a basaltic lava flow forming the base of Mesa Mistemeque, 20 km west of Río Grande de Santiago (Nieto *et al.*, 1985).

The RSMS is overlain by the 4.8 Ma S. Gaspar Ignimbrite (Gilbert *et al.*, 1985) and other Plio-Quaternary acidic rocks that underlie Guadalajara city (Spinnler *et al.*, in press); it decreases in thickness towards the north and pinches out against the early Miocene andesites and ignimbrites of the SMO about 40 km north of Guadalajara (Figure 1).

The RSMS is also well exposed in the Río Verde valley, 25 km northwest of Tepatitlán (Figure 1) where it is about 220 m thick (Figure 2b) and yielded ages of 10-9.5 Ma (sample 13 to 16 in Table 1). In this area the RSMS is covered by small lava cones of uncertain age. It rests unconformably over a 50 m thick microconglomerate that overlies SMO ignimbritic units (28 Ma; Table 1). In the Arandas area, Verma *et al.* (1985) obtained slightly older dates for the RSMS (sample 11 and 12 in Table 1), whereas a date of 24.1 Ma was found for the underlying SMO ignimbrites (sample 2 in Table 1). South of Guadalajara, the southern part of the RSMS is overlain by an ignimbritic unit with distinctive dark glassy *fiamme* up to 10 cm in size. This unit, already recognized by Demant (1981), was later studied by Gilbert *et al.* (1985) who obtained ages of 7.7 and 7.1 Ma (sample 24 and 27 in Table 1).

South of Guadalajara the RSMS has been disrupted and downdropped by the extensional fault system of the Chapala rift. It may be recognized as tilted blocks partly covered by younger volcanics (Garduño *et al.*, in press). On the northern shore of the Lake Chapala this basaltic sequence is about 170 m thick and rests in unconformity over a highly altered sequence of andesites and breccias with lava blocks ranging between 10 and 50 cm in size (Figure 2c). Basaltic flows possibly related to the RSMS southwest of La Piedad (Figure 1) have been dated 8.8 Ma (Rosas *et al.*, 1989; 21 in Table 1) whereas an age of 10.1 Ma has been reported for an andesitic ridge about 18 km SE of Lake Chapala (Allan, 1986).

The present area of the RSMS is approximately 8500 km^2. The southern end of the plateau is hidden under the Plio-Quaternary volcanic units. Nevertheless, if we consider the outcrops on the shores of Chapala lake as the southernmost part of the plateau we can estimate that the total extent should be on the order of 15.000 km^2; assuming an average thickness of 200 m, about 3.000 km^2 of mafic magma erupted in about 3.5 Ma in the area east of Guadalajara, with an average output rate of 0.8 km^3 / 1000 years.

QUERÉTARO - SAN JUAN DEL RIO AREA

East of latitude 102° W, late-Miocene volcanic rocks are more widely scattered than in the Guadalajara-Arandas area. The best preserved outcrops can be found near Querétaro, where a basaltic plateau extends several tens of kilometers with a mean elevation of 1950 m a.s.l. (Figure 1). These volcanic rocks, hereafter referred to as the Querétaro mafic sequence (QMS), have a total thickness not exceeding 20 m and consist mainly of thin lava flows that overlie several tens of meters of fluvial and lacustrine deposits with intercalated pyroclastic flow and pumice fall units (Figure 2d). A K-Ar date of 8.1 Ma was obtained for a basaltic sample collected at the base of the sequence, near Querétaro (32 in Table 1). Toward the south, the QMS is covered by two ignimbritic units dated 6.1 and 3.8 Ma, respectively, which are related to the Los Azufres and the Amealco calderas (Figure 1 and 2d; Ferrari *et al.*, 1991).

West of Querétaro, some small basaltic and andesitic mesas rest on continental sedimentary deposits (Figure 2e) or directly on SMO rhyolites and ignimbrites dated 23.2 Ma and 22.4 Ma, respectively (Pasquarè *et al.*, 1991; 28 and 29 in Table 1). The continental deposit is a coarse and poorly fluvial consolidated conglomerate with

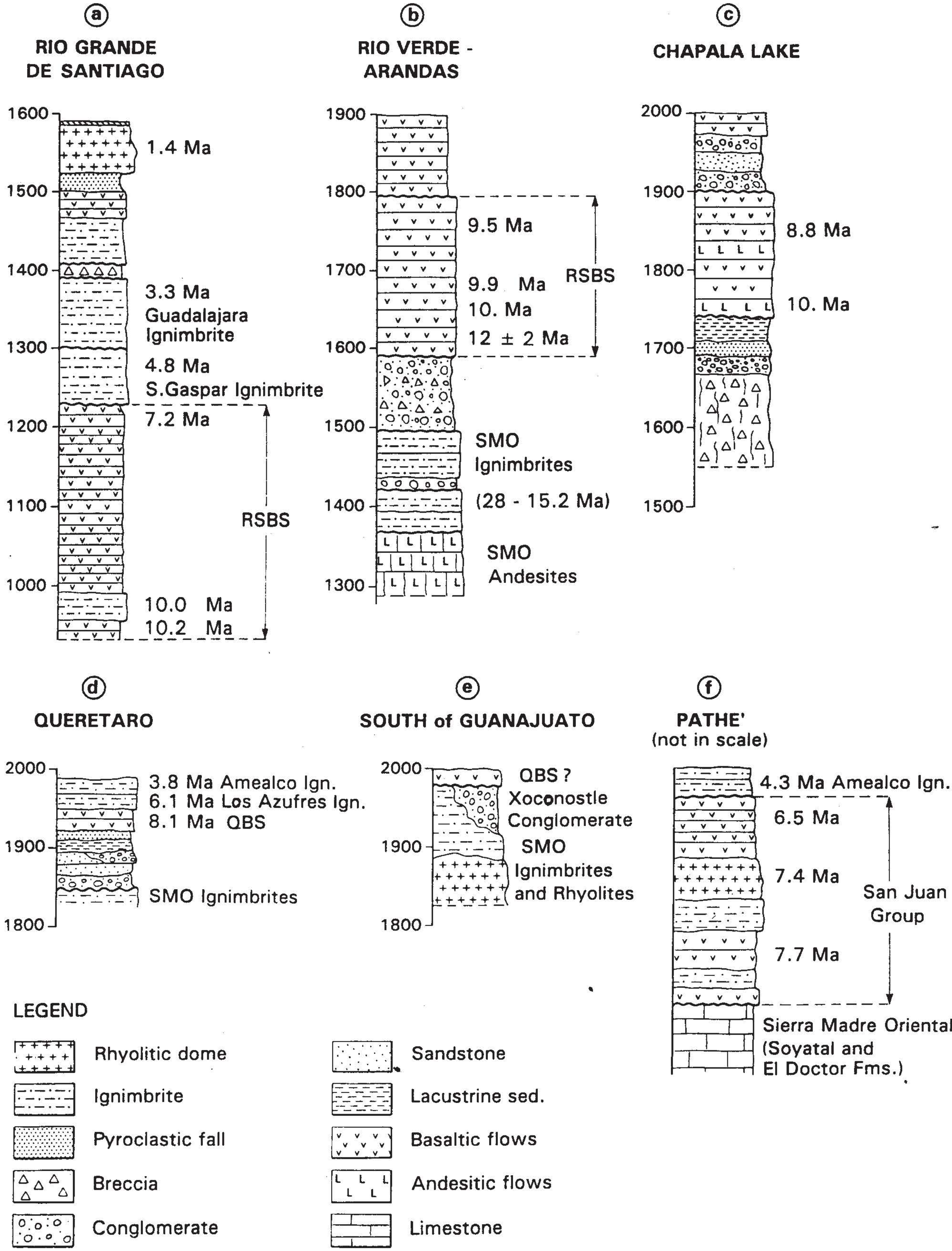

Fig. 2. Stratigraphic sections and relative radiometric ages of representative areas in the study region. Numbers on the left of columns are elevations in m a.s.l.

Table 1

Pre-Pliocene radiometric dates for the studied area

	Sample	Rock type	Longitude	Latitude	Age	Error	Source *
			Guadalajara - Arandas area				
1	Ped 16	Ignimbrite	102.77	21.08	28.0	1.2	1
2	DCH 1	Ignimbrite	102.02	20.67	24.1	0.8	2
3	W 4	Andesite	103.47	21.32	21.0	1.0	3
4	Ped 10	Basalt	103.23	21.12	20.9	0.4	1
5	S 1	Basalt	102.20	20.67	12.0	2.0	4
6	S 6	Bas.-and.	102.53	20.68	11.0	2.0	4
7	DCH 2	Basalt	102.23	20.58	10.8	0.9	2
8	-	Basalt	(1)	(1)	10.2	0.8	5
9	1131	Basalt	102.31	20.70	10.2	0.3	6
10	M203a	Andesite	103.45	20.06	10.1	0.4	7
11	-	Ignimbrite	(1)	(1)	10.0(2)	0.04	5
12	C3	Bas.-and.	103.17	21.02	10.0	1.0	3
13	S 8	Basalt	102.43	20.76	10.0	2.0	4
14	Ped 14	Basalt	102.85	20.87	10.0	-	1
15	Ped 12	Basalt	102.90	20.84	9.6	0.3	1
16	1	Basalt	103.31	20.85	9.5	0.1	8
17	2	Basalt	103.33	20.85	9.2	0.1	8
18	DCH 5	Basalt	102.35	20.47	9.3	0.9	2
19	3	Ignimbrite	103.31	20.83	9.1	0.1	8
20	4	Basalt	103.33	20.81	9.0	0.2	8
21	Roe 142	Basalt	102.39	20.03	8.8	0.8	9
22	Ped 12	Basalt	103.12	20.80	8.0	0.1	1
23	Ped 11	Basalt	103.23	20.77	8.0	0.1	1
24	KA 4289	Ignimbrite	103.03	20.71	7.7	0.2	10
25	W 2	Basalt	103.42	21.03	7.5	2.0	3
26	W3	Andesite	103.42	21.12	7.3	2.0	3
27	KA 3100	Ignimbrite	103.32	20.78	7.1	0.2	10
			Queretaro - San Juan del Rio area				
28	Mx88 38	Rhyolite	101.22	20.93	23.3	1.0	11
29	Mx88 41	Ignimbrite	101.02	20.87	22.4	1.0	11
30	ZI 43	Andesite	99.40	20.78	9.0	0.3	12
31	HF 7	Andesite	99.60(3)	20.50(3)	9.0	0.8	13
32	Mx88 20	Basalt	100.37	20.62	8.1	0.8	11
33	Cu 8	Andesite	101.16	19.76	7.8	0.4	11
34	HF 24	Rhyolite	99.72(3)	20.64(3)	7.8	0.4	13
35	-	Basalt	99.60(3)	20.60(3)	7.7(2)	0.1	14
36	HF 25	Rhyolite	99.72(3)	20.64(3)	7.6	0.3	13
37	-	Rhyolite	99.74(3)	20.61(3)	6.7	0.1	15
38	-	Basalt	99.74(3)	20.61(3)	6.5	0.2	15
39	Pu 3	Basalt	101.54	20.02	6.0	0.4	11
40	Cl 14	Basalt	101.45	19.96	5.6	0.3	11

(*) 1= Nieto et al., 1981; 2 = C.F.E., 1991; 3 = Spinnler et al., in press; 4 = Verma et al., 1985; 5 = Moore and Carmichael, 1991; 6 = Nixon et al., 1987; 7 = Allan, 1986; 8 = Watkins et al., 1971; 9 = Rosas-E. et al., 1989; 10 = Gilbert et al., 1985; 11 = Pasquarè et al., 1991; 12 = Cantagrel and Robin, 1979; 13 = Venegas et al., 1985; 14 = Suter et al., 1992; 15 = Nichols, 1970.

(1) Rio Grande de Santiago, 30 km north of Guadalajara.

(2) $^{39}Ar/^{40}Ar$ date.

(3) Approximate location.

clasts of ignimbrite and less andesite, and with minor intercalations of lacustrine sandstones. This unit, named Xoconostle conglomerate by Pasquarè *et al.* (1991), represents an erosional product of the SMO volcanic pile exposed to the north. Some of the basaltic mesas cropping out west of Querétaro may be older than the QMS.

A basaltic plateau that can be correlated with the QMS is found east of Querétaro between San Juan del Río and the Pathé area (Figures 1 and 2f), where some tens of meters of olivine basalts overlie rhyolites and ignimbrites dated at 7.8 and 7.6 Ma (Milan and Herrera, 1987; Venegas *et al.*, 1985). The uppermost basalts have been dated 6.5 Ma (38 in Table 1). About 20 km east of Pathé, where the plateau rests directly on the late-Cretaceous limestones of the Sierra Madre Oriental, a basalt sample furnished a $^{39}Ar/^{40}Ar$ age of 7.7 Ma (Suter *et al.*, 1992). About 10 km east of the area covered by this study, an isolated mesa of andesite was dated at 9 Ma (Cantagrel and Robin, 1979).

North and west of Cuitzeo lake the QMS is 150m thick and consists of basaltic flows that have been dated at 6.0 and 5.6 Ma (39 and 40 in Table 1). Here the QMS was preceded by a sequence of lava flows and domes, dominantly of andesitic composition, which mainly crop out south of the study area between Cuitzeo lake and Morelia. The base of this pre-plateau sequence is not recognizable; an andesitic sample from its upper part was dated at 7.8 Ma (34 in Table 1).

At present the QMS covers an area of about 3800 km^2 with thicknesses ranging from 20 to 150 m. The extensive Plio-Quaternary volcanism and faulting in this area prevent any evaluation of the original extent of the late-Miocene mafic volcanic products; however, if we assume a continuous volcanic cover from Querétaro to Cuitzeo lake, the original extent may have been more than twice the present one, with a volume comparable to the RSMS.

TECTONIC SETTING

A comprehensive study of the tectonic regime that accompanied late-Miocene mafic volcanism will be carried out in a future study. Here we present a preliminary account of the tectonics in the investigated area.

The mafic volcanic sequences described in the previous sections were emplaced in an E-W elongated belt bounded in the north by the SMO and in the south by the Plio-Quaternary products of the MVB. The RSMS was largely emplaced between 11 and 7.5 Ma, after a period of volcanic quiescence marked by various erosional deposits; around Lake Chapala, however, it overlies an older andesitic sequence. The top of the RSMS is at an elevation of about 1900 m a.s.l., which is 200-400 m lower than the SMO ignimbritic plateaux to the north. This means that, south of Latitude 21°N, the SMO was tectonically downfaulted by E-W trending faults after the early Miocene (Figure 1). In the field, these faults are largely covered by the RSMS. Yet some E-W normal faults are still visible along the Río Verde, NW of Arandas (Figure 1), and some kilometers north of the Río Grande de Santiago canyon (Spinnler *et al.*, in press). South of Arandas, the late-Miocene plateau was downthrown by the E-W trending normal faults of the Chapala rift, which mostly developed between 7 and 3.5 Ma (Delgado, 1992). In some outcrops of pre-plateau andesites these E-W normal faults show an early left-lateral transcurrent motion (Garduño *et al.*, in press). Therefore these faults probably formed in the middle-Miocene, with a left-lateral strike-slip motion, and were later reactivated with a dominant dip-slip motion in late-Miocene and early-Pliocene times (Ferrari *et al.*, this issue). We can tentatively hypothesize that normal faulting shifted progressively to the south; in an early phase, during the late Miocene, this faulting produced the depression of the SMO and the emplacement of the RSMS; subsequently, during the early Pliocene, it formed the Chapala rift and permitted the emplacement of the remaining MVB products.

In the Querétaro area, a relatively thin basaltic plateau formed between 8.1 and 6.5 Ma in an area occupied by lacustrine basins. Thicker basaltic sequence was emplaced to the south, in the Cuitzeo area, between 6 and 5.6 Ma, over an older andesitic sequence. West of Querétaro, the SMO volcanic rocks disappear under the Quaternary alluvial deposit of the Salamanca depression along the NW-trending Sierra de Guanajuato normal fault system (Henry and Aranda, 1992). In the Querétaro area, the QMS plateau is cut by the NNW-trending Querétaro-Taxco fault system (Pasquarè *et al.*, 1988), which represents a reactivation of the old suture between the Mesozoic volcanic arcs of the Guerrero Terrane (Cordilleran domain) and the Sierra Madre Oriental Terrane (Tethyan domain)(Campa and Coney, 1983). The presence of lacustrine basins along the Querétaro-Taxco fault system suggests that it could have also controlled emplacement of the QMS in late-Miocene times.

PETROGRAPHY AND GEOCHEMISTRY

Major and trace element analyses of selected samples are given in Tables 2-4. According to the previously discussed stratigraphy, the samples of late-Miocene age were divided into three groups: 1) pre-plateau, which includes the andesitic succession of Chapala lake and the mesas west of Querétaro, 2) plateau lavas, and 3) post-plateau lavas, including the small lava cones mainly located in the Guadalajara region (Figure1).

On the whole, the studied samples define a subalkaline association (Figure 3), with a calcalkaline affinity, as shown by the FeO^*/MgO ratios and by relatively high Al_2O_3 contents. K_2O contents are typical of normal calcalkaline series as displayed in Figure 4, where only few samples fall in the high-K calcalcaline field.

The plateau lavas are little evolved and are mostly relatively primitive basalts (Mg# 66-52). Pre- and post-

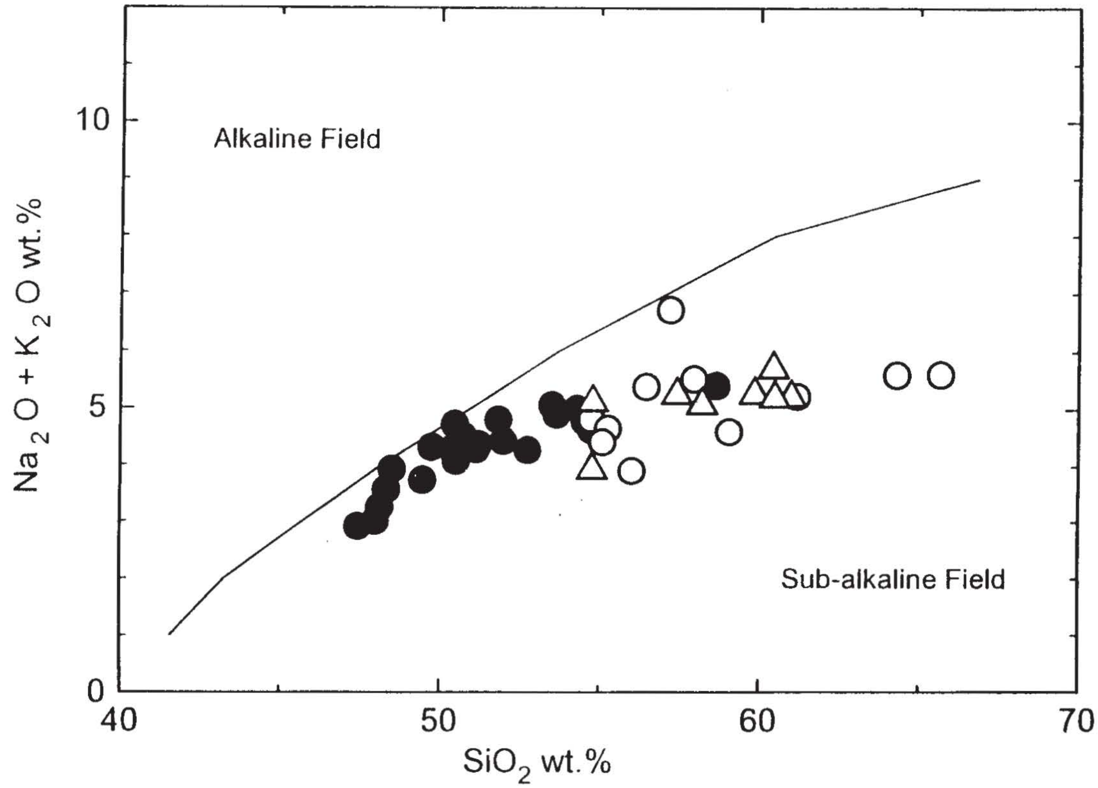

Fig. 3 - Alkali-SiO_2 diagram. FILLED CIRCLES = RSMS-QMS plateau lavas; OPEN CIRCLE = post-plateau lavas; OPEN TRIANGLE = pre-plateau lavas. Dividing line from Irvine and Baragar (1971).

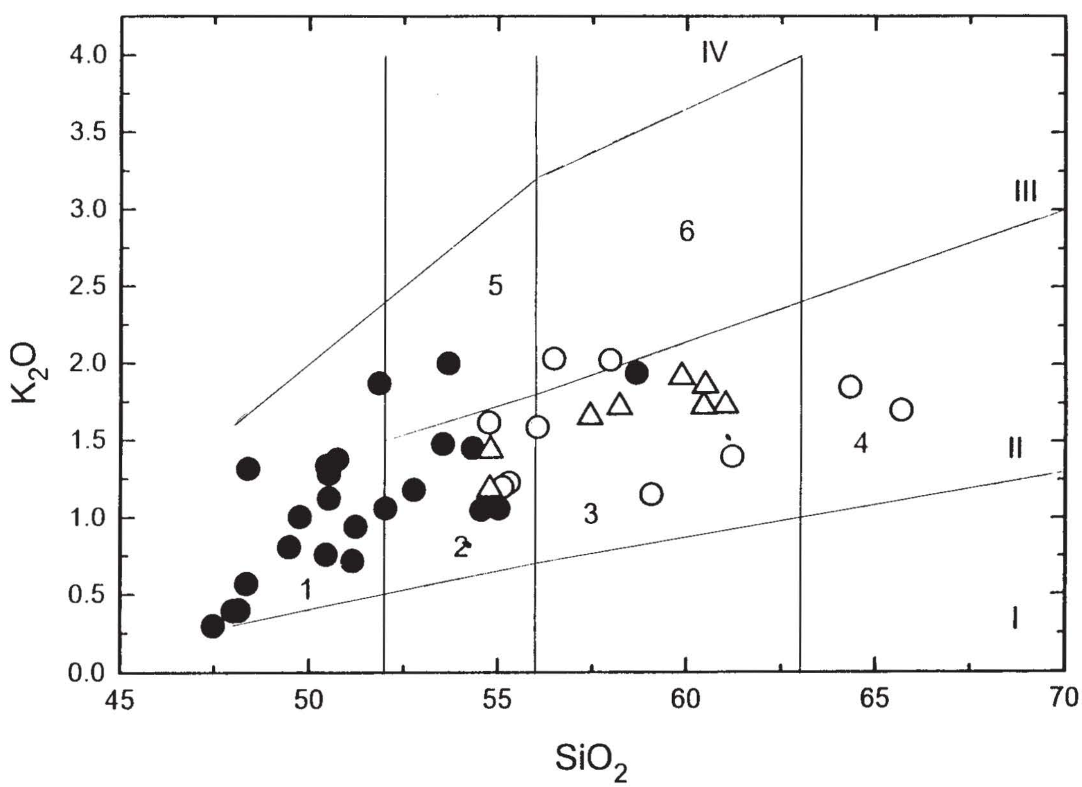

Fig. 4 - K_2O-SiO_2 classification diagram after Peccerillo and Taylor (1976). I, island-arc tholeiitic series; II, calc-alkaline series; III, high-K calc-alkaline series; IV, shoshonitic series. 1 = basalt; 2 = basaltic andesite; 3 = andesite; 4 = dacite; 5 = high-K basaltic andesite; 6 = high-K andesite. Symbols as in Fig. 3

Table 2

Major and trace elements of pre-plateau lavas

SAMPLE	Chapala-Quitzeo MQ40	MQ48	MQ49	MQ50	MQ54	Queretaro-Penjamo MQ11	MQ10	MQ12	MQ9
SiO2	53.67	54.81	57.43	60.43	60.48	58.21	59.85	54.79	61.00
TiO2	1.95	1.33	1.09	0.77	0.81	1.07	1.02	0.82	0.92
Al2O3	16.40	17.75	17.16	17.54	16.99	17.34	16.29	16.63	17.01
Fe2O3	2.64	2.85	4.03	2.78	1.66	4.26	3.87	3.00	2.77
FeO	6.65	5.58	3.06	3.18	4.00	2.00	1.84	4.32	2.66
MnO	0.15	0.13	0.12	0.10	0.12	0.10	0.09	0.12	0.10
MgO	4.53	4.31	3.23	2.68	3.48	3.95	2.59	6.48	2.88
CaO	7.26	7.41	6.94	6.30	6.39	7.04	6.94	8.02	6.49
Na2O	2.91	3.70	3.65	3.99	3.36	3.38	3.41	2.79	3.51
K2O	2.02	1.44	1.68	1.73	1.87	1.73	1.95	1.20	1.74
P2O5	1.03	0.31	0.17	0.18	0.16	0.22	0.31	0.27	0.24
L.O.I.	0.79	0.38	1.44	0.32	0.68	0.70	1.84	1.56	0.68
V	196	205	168	143	156	165	145	222	134
Cr	91	74	33	36	40	49	28	302	30
Co	30	31	25	21	18	20	16	28	16
Ni	27	55	40	39	9	14	9	33	8
Rb	52	22	29	30	60	25	25	17	25
Sr	508	616	651	738	680	1217	1173	1088	1234
Y	37	20	15	15	18	18	16	14	19
Zr	305	140	129	121	126	148	179	77	154
Nb	7	12	9	5	5	6	4	4	3
Ba	1089	546	751	693	527	587	714	520	750
La	59	18	15	26	23	27	30	20	36
Ce	89	46	40	49	51	68	69	50	76
Mg #	50.37	51.69	49.41	48.82	56.16	57.79	49.59	65.12	53.06

Major elements: XRF with full matrix effect correction after Franzini *et al.* (1972), except MgO and Na_2O by AAS, FeO by Titration. L.O.I., loss on ignition (~1000°C). Trace elements: XRF, according to Leoni and Saitta (1976) method. Mg#=Mg/(Mg+Fe^{2+}) atomic ratio, assuming Fe_2O_3/FeO=0.15.

plateau rocks are more evolved and have mainly andesitic compositions (Figure 4).

The basalts feature porphyritic to subaphyritic textures. Zoned plagioclase (An 76-59) and normally zoned olivine (Fo 85-79) are the main phenocryst phases. Olivine is also generally present in the groundmass, where it is richer in Fe (Fo 75-50). Commonly, it is partially or totally replaced by iddingsite. Plagioclase and olivine are sometimes found as glomeroporphyritic aggregates. Clinopyroxene, less abundant than olivine and plagioclase, is variably represented by augite and aluminous-ferrous augite (Wo 46-41, Fs 14-12). It is slightly zoned, with rims richer in Fe than the cores (Fs 15-20) and is compositionally similar to the groundmass grains. An enstatitic pyroxene (Fs 22-34) is occasionally found in the samples with higher SiO_2 contents. The groundmass varies from holocrystalline to hypocrystalline, with subophitic or intersertal textures. It contains the same minerals as the phenocrysts, in addition to Ti-magnetite and subordinate ilmenite. Carbonates are the most widespread secondary minerals. They are observed both as alteration products of femic minerals and as grains filling veins or vacuoles.

In the basaltic andesites, the phenocrysts are represented by plagioclase, two pyroxenes, and rare olivine that is absent in the groundmass. Commonly the olivine phenocrysts show pyroxene reaction rims. The cpx/opx ratio decreases with increasing SiO_2 content. Pre- and post-plateau lavas are generally represented by andesites. They are always porphyritic, with plagioclase, clinopyroxene, and orthopyroxene phenocrysts. Ti-magnetite generally occurs as microphenocrysts. A hydrous phase, presumably amphibole, completely transformed into aggregates composed of Fe-Ti oxides and pyroxenes, is observed in sample MQ9. In the few dacites, orthopyroxene is the dominant or only femic phase. The groundmass is formed by plagioclase, pyroxene, opaque minerals, and glass in variable amounts. Biotite sometimes occurs as the last crystallizing phase.

The chemical variations of the studied sequence are shown in the Harker diagrams of Figure 5. The varia-

Table 3

Major and trace elements of Arandas-Queretaro plateau lavas

SAMPLE	MQ20	MQ18	MQ19	MQ33	MQ44	MQ17	MQ16	MQ3	MQ24	MQ13	MQ15	MQ21	MQI	MQ22	MQ38	MQ53	MQ45	MQ51	MQ55	MQ34	MQ28	MQ4	MQ35
SiO2	47.46	48.00	48.16	48.35	48.52	49.47	49.74	50.44	50.46	50.52	50.54	50.73	51.15	51.22	51.85	51.99	52.77	53.53	54.32	54.56	54.78	55.02	58.66
TiO2	1.24	1.01	1.25	1.14	1.69	1.29	1.52	1.79	1.53	1.37	1.45	1.58	1.81	1.83	1.35	1.15	1.31	1.32	1.51	1.07	1.03	1.44	1.15
Al2O3	15.96	16.5	17.04	18.59	17.35	17.16	17.57	17.93	17.77	17.31	17.69	17.40	18.39	17.15	16.43	17.51	16.26	17.56	17.81	18.38	18.15	17.64	16.71
Fe2O3	6.76	6.11	6.70	2.09	2.46	3.48	5.41	5.89	3.24	3.13	4.23	4.80	4.85	7.02	4.38	3.66	5.71	2.65	2.77	2.81	3.67	3.05	2.47
FeO	4.14	4.10	3.34	6.74	7.73	5.78	4.84	4.12	7.04	6.54	5.26	4.90	4.90	3.56	5.70	5.04	3.70	5.64	5.72	4.86	4.56	4.92	4.14
MnO	0.15	0.14	0.14	0.14	0.16	0.12	0.15	0.16	0.17	0.16	0.16	0.15	0.16	0.14	0.14	0.14	0.14	0.14	0.14	0.13	0.12	0.13	0.11
MgO	9.15	8.75	8.82	7.46	7.47	7.96	6.60	5.49	5.31	6.70	6.01	5.98	5.54	4.21	6.21	6.15	5.11	5.5	4.03	4.75	4.12	4.64	2.92
CaO	8.84	8.61	8.52	10.15	8.17	9.30	8.25	8.51	9.31	9.59	8.84	8.68	8.57	8.48	7.87	9.09	8.74	8.14	7.88	7.61	8.17	7.17	5.94
Na2O	2.70	2.70	2.93	3.05	3.38	2.97	3.35	3.52	3.39	2.96	3.09	3.16	3.56	3.48	2.95	3.38	3.13	3.59	3.57	3.75	3.51	3.52	3.54
K2O	0.31	0.41	0.41	0.58	0.63	0.82	1.02	0.77	1.34	1.13	1.30	1.39	0.72	0.96	1.89	1.07	1.20	1.48	1.46	1.06	1.14	1.07	1.98
P2O5	0.15	0.23	0.20	0.21	0.46	0.23	0.39	0.38	0.39	0.25	0.37	0.41	0.33	0.31	0.41	0.24	0.47	0.41	0.33	0.24	0.21	0.55	0.45
L.O.I.	3.14	3.44	2.49	1.5	1.98	1.42	1.16	1.00	0.05	0.34	1.06	0.82	0.02	1.64	0.82	0.58	1.46	0.04	0.46	0.78	0.54	0.85	1.93
V	206	171	201	204	226	232	232	193	251	254	213	250	192	325	256	214	206	199	201	200	199	145	166
Cr	291	210	331	229	156	232	239	93	142	219	204	217	117	97	299	247	127	164	71	90	123	119	18
Co	48	44	45	41	43	40	41	36	42	40	44	37	37	36	42	37	33	33	30	29	30	26	20
Ni	190	142	193	121	110	121	119	39	73	72	74	96	79	27	143	134	72	106	43	47	60	40	14
Rb	2	3	4	7	6	17	18	6	41	46	33	22	6	15	40	16	20	22	22	17	17	12	73
Sr	334	355	354	353	417	450	525	505	478	395	393	470	571	537	521	594	606	786	684	537	582	614	564
Y	18	19	19	20	25	20	24	24	40	27	127	24	24	22	20	19	23	19	19	18	15	24	24
Zr	105	97	104	108	179	131	164	175	180	179	180	199	164	138	214	110	182	141	170	101	99	238	256
Nb	4	2	2	4	4	4	9	9	9	6	5	7	8	7	8	4	9	8	15	5	3	9	10
Ba	130	157	170	211	300	298	469	706	705	423	501	540	518	416	737	595	558	693	790	391	547	687	845
La	4	7	5	9	14	13	23	15	25	12	49	18	15	14	30	14	25	25	23	12	12	24	33
Ce	23	23	23	19	38	32	46	33	42	33	46	40	46	40	68	36	51	55	53	26	32	59	69
Nd				13		17	24					22								13			
Sm				4.1		4.9	7.4					6.7								3.7			
Eu				1.34		1.53	1.99					1.95								1.25			
Tb				0.66		0.77	0.91					0.9								0.79			
Yb				2.5		2.4	3.0					3.0								1.95			
Lu				0.41		0.42	0.4					0.49								0.46			
Th				0.6		2.8	2.4					2.0								1.7			
Ta				0.23		0.4	0.8					0.55								0.6			
Hf				2.8		3.0	3.8					5.4								3.2			
Mg#	64.41	64.83	65.56	63.63	60.30	64.36	57.89	54.09	51.89	59.15	57.27	56.74	54.73	46.29	56.57	59.88	53.90	58.09	49.81	56.52	51.45	55.04	48.13

Analytical methods as in Table 2. La and Ce by XRF when the other REE not determined. REE, Th, Ta and Hf by INAA (Poli et al., 1977).

Table 4

Major and trace elements of post-plateau central volcano lavas

SAMPLE	MQ25	MQ42	MQ41	MQ31	MQ32	MQ27	MQ56	MQ30	MQ14	MQ6	MQ5
SiO2	54.76	55.11	55.30	56.04	56.47	57.21	57.95	59.07	61.18	64.30	65.67
TiO2	1.16	1.04	0.97	0.93	0.85	1.09	1.11	0.91	0.88	0.81	0.77
Al2O3	18.32	17.27	17.98	18.44	18.57	16.15	17.24	17.80	17.01	16.50	15.90
Fe2O3	3.92	3.97	3.23	3.93	2.87	4.87	2.07	3.84	2.72	1.69	2.34
FeO	3.84	3.60	4.25	2.94	3.04	1.56	4.78	2.02	3.08	2.76	2.08
MnO	0.13	0.14	0.12	0.11	0.10	0.08	0.11	0.09	0.10	0.07	0.07
MgO	4.15	4.91	4.79	4.71	3.99	4.10	4.36	3.85	2.86	2.03	1.90
CaO	7.35	7.38	7.55	7.49	6.97	6.57	6.44	6.92	5.95	4.58	4.52
Na2O	3.23	3.27	3.45	2.35	3.39	3.06	3.50	3.47	3.85	3.80	3.94
K2O	1.64	1.22	1.24	1.61	2.06	3.72	2.03	1.16	1.41	1.88	1.72
P2O5	0.37	0.35	0.33	0.24	0.49	0.60	0.25	0.19	0.28	0.15	0.16
L.O.I.	1.13	1.74	0.79	1.21	1.20	0.99	0.16	0.68	0.68	1.43	0.93
V	165	173	169	164	136	177	139	149	128	70	68
Cr	53	119	141	100	41	66	119	60	35	18	20
Co	25	28	28	23	22	22	25	20	19	12	12
Ni	27	59	71	44	41	66	61	33	22	8	7
Rb	33	26	19	21	36	67	42	10	17	48	33
Sr	808	690	608	1024	1181	1610	458	1116	757	442	454
Y	43	17	16	38	19	19	28	10	14	16	16
Zr	135	123	113	85	161	341	248	50	89	139	154
Nb	4	5	4	4	4	4	15	3	3	6	7
Ba	642	651	0	816	768	698	607	412	481	615	616
La	48	23	0	45	43	44	33	14	12	17	20
Ce	-	47	0	45	76	103	66	34	31	41	45
Nd	34										
Sm	7.8										
Eu	1.81										
Tb	1.14										
Yb	3.3										
Lu	0.56										
Th	2.5										
Ta	0.5										
Hf	4.1										
Mg#	53.25	58.06	57.51	59.52	58.93	58.25	57.03	58.71	51.13	48.95	47.86

tions are typical of orogenic series with a general decrease in FeOtot, CaO, MgO, TiO_2 and an increase in Na_2O and K_2O with increasing SiO_2. The relatively wide scattering of values observed in the Harker diagrams can be attributed to the frequent occurrence of phenocrysts, which are subject to concentration and depletion, and to the large time span covered by the sampled rocks.

As far as the plateau rocks are concerned, the increase of Na_2O and K_2O is accompanied by an increase of Al_2O_3, (except for three andesitic-basalt samples with relatively low Al_2O_3 contents), and by a sharp decrease of MgO; CaO shows a negative correlation with SiO_2. This subset of samples does not display any Fe-enrichment; however, in the most primitive rocks iron decreases slightly comparated with moderately evolved rocks (MgO ~5.5%); this behaviour is reflected also in the Ti-distribution that shows a weak increase up to 5.5% MgO, followed by a drastic decrease. Trace elements (Figure 6 a, b) show a negative correlation between SiO_2 and the compatible elements Co, Cr and Ni, whereas V exhibits a slight increase up to SiO_2 about 52%, similar to the Ti distribution. In contrast, Sr, Rb, Ba and La increase with SiO_2 contents, as well as the more scattered Ce, Zr and Nb.

In the pre- and post-plateau lavas trace elements generally show more dispersed values; a negative correlation is recognizable for the ferromagnesian elements and, less clearly, for Zr, Nb, La, Ba and Y. Also Sr and Rb tend to decrease starting from SiO_2 contents around 55-60%.

As a whole, these variations suggest that fractional crystallization of femic minerals played a major role in

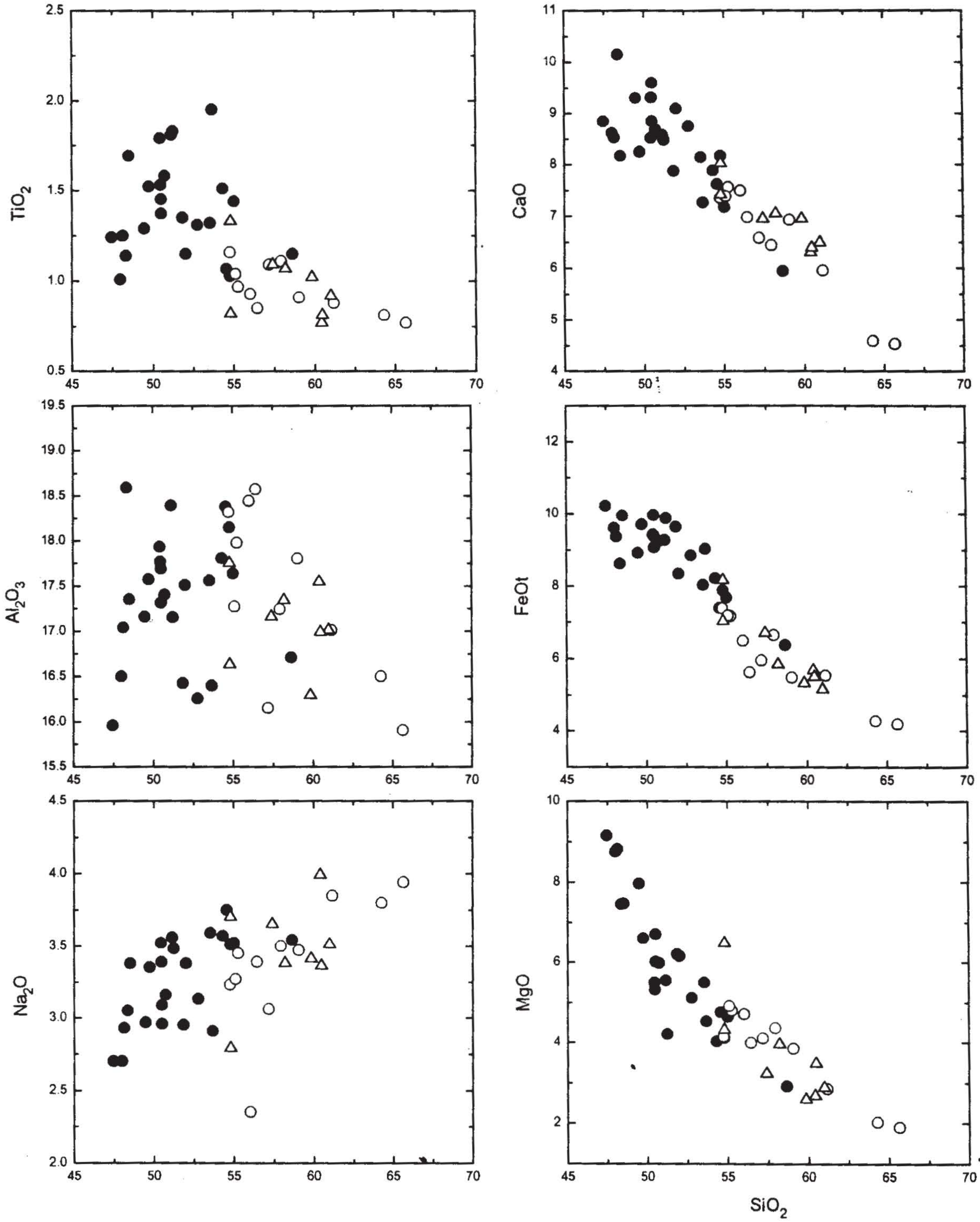

Fig. 5 - Variation diagrams for major elements versus SiO_2 wt%. Symbols as in Fig. 3.

the evolution of the sequence. Plagioclase seems to play a secondary role, at least up to the appearence of the basaltic andesites, as evidenced by the alkali and Sr increment. Tentatively, we interpret these features as a result of differentiation processes that occurred at different levels of the continental litosphere in response to different tectonic regimes. The chemical variations of plateau lavas could reflect fractional crystallization under relatively high-P conditions, possibly at the base of the continental crust or at the mantle-crust boundary according to the model of Meen (1990). The pre- and post-plateau lavas, mainly connected with central volcanoes, were generated

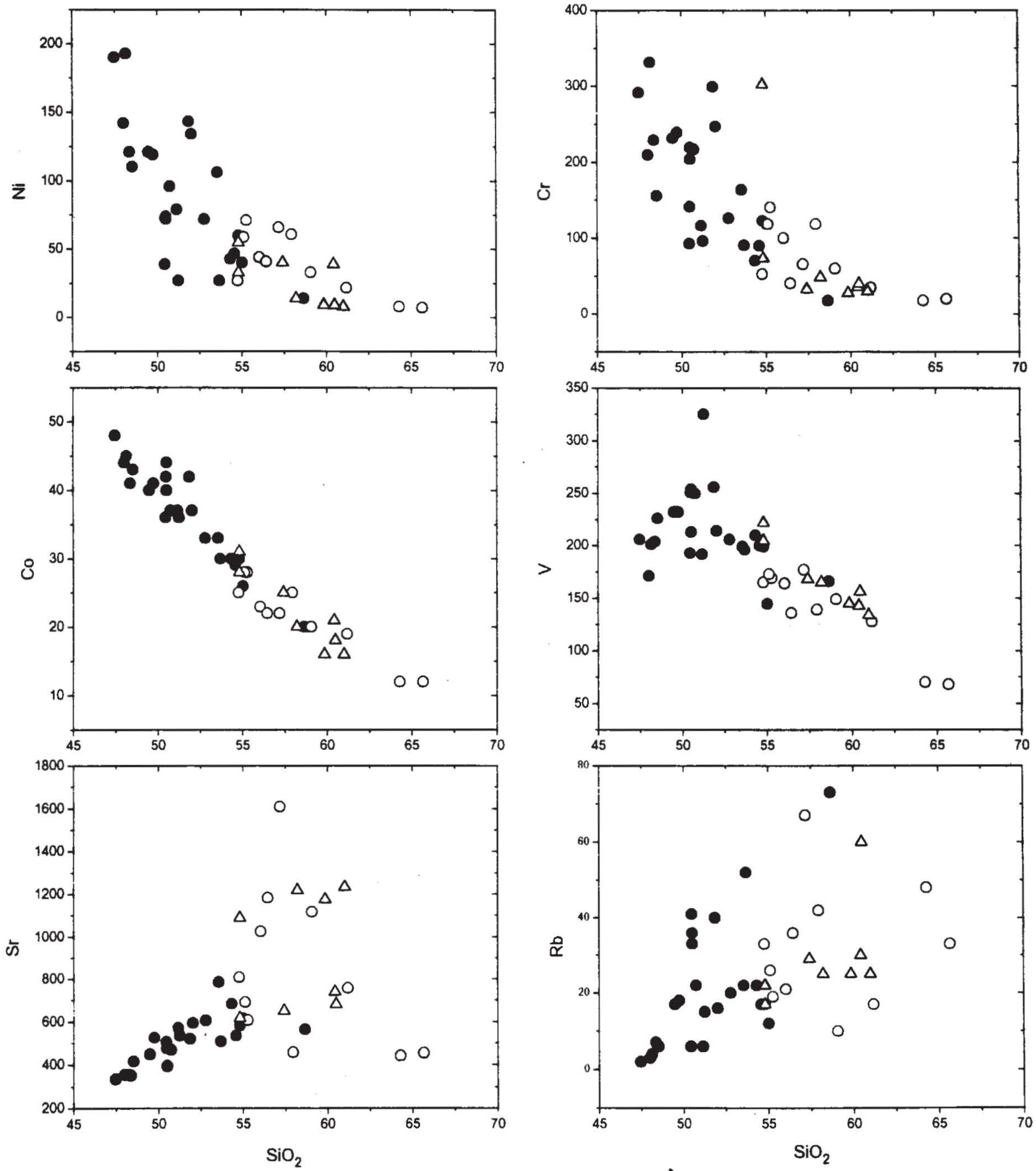

Fig. 6a - Variation diagram of trace elements versus SiO_2 wt%. Symbols as in Fig. 3.

at different levels in the continental crust, where the plagioclase played an important role in the differentiation process.

REE patterns of selected plateau basalts and andesitic basalts are shown in Figure 7. HREE appear poorly fractionated, whereas LREE seem variably fractionated. In particular, the LREE fractionation increase with the degree of the evolution, disregarding basaltic andesite MQ34.

In the spider diagram of Figure 8 the distribution of trace elements normalized to primodial mantle (Wodd, 1979) is shown. They display a typical calcalkaline pattern with a high LILE/HFSE ratios and negative Th, Ta, Nb and Ti anomalies and small, but significant positive Sr anomalies. Also in the discriminant diagram of Figure 9, the plateau and post-plateau samples fall within the calcalcaline field.

CONCLUSIONS

Large basaltic plateaux were emplaced between 10.5 and 5.6 Ma in the Guadalajara-Arandas and Querétaro-San Juan del Río areas. This mafic volcanism consists of relatively primitive basalts that did not undergo significant

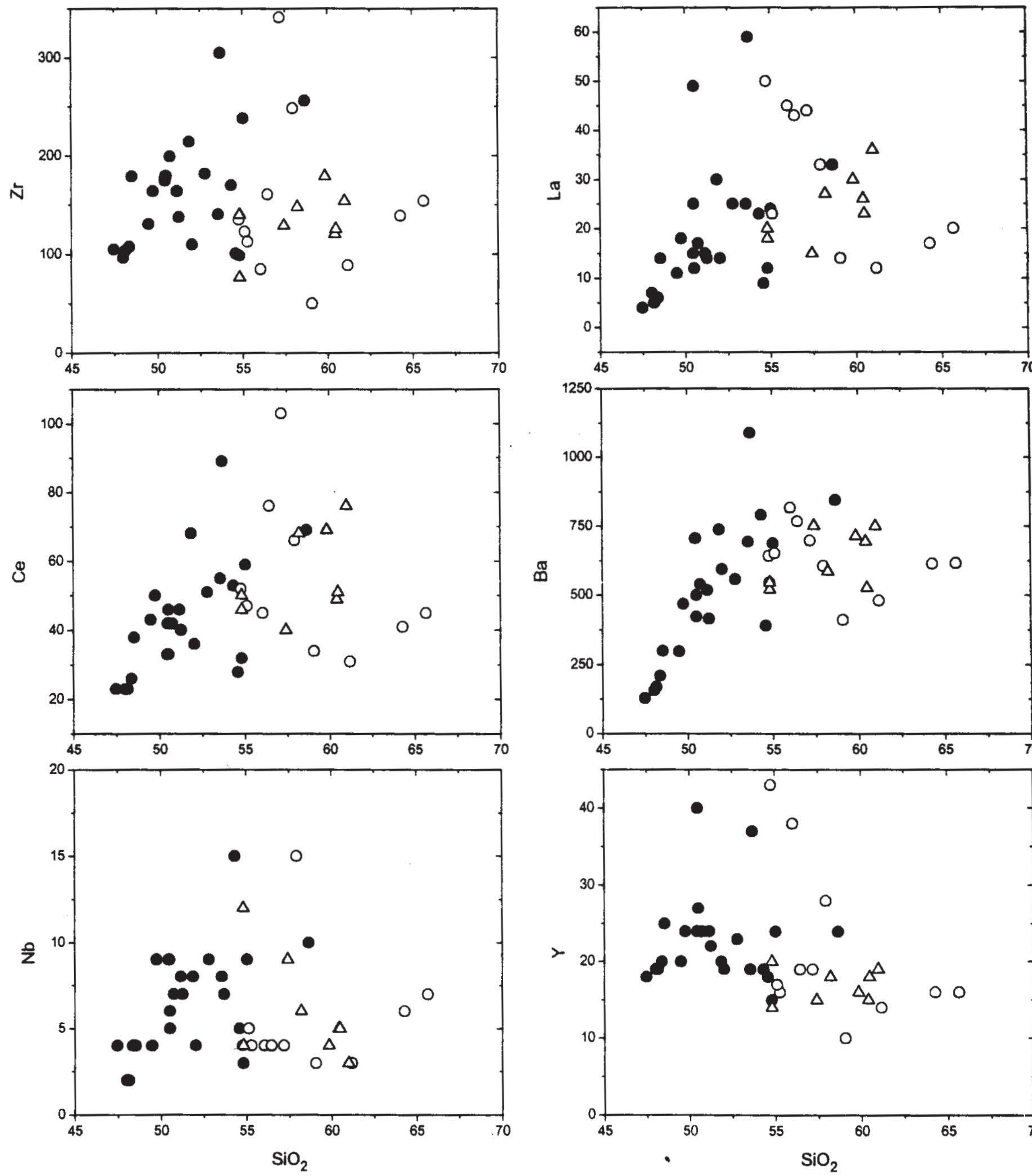

Fig. 6b (cont).

low-P fractionation and that display a clear orogenic affinity. In the northern part of the study region these volcanics are separated by the late-Oligocene-early Miocene SMO ignimbrites and andesites by various erosional deposits whereas in the southern part they overlie andesitic sequences of middle- to late-Miocene age. The estimated original extent of these rocks in the Guadalajara-Arandas area is about 8500 km^2, and their volume can be evaluated as about 3000 km^3. Similar values can be calculated in the the Querétaro-San Juan del Río area. These figures give an output rate of 0.8 km^3/1000 years for each area. An identical value has been calculated by Hasenaka and Carmichael (1985) for the Quaternary Michoacán-Guanajuato volcanic field of the MVB, which has a comparable areal extent.

The results presented in this work provide insight into the geodynamic significance of the late-Miocene mafic volcanism of central Mexico and its relationship to the MVB. The Pacific convergent margin of Mexico has been characterized by continuous volcanic activity since the Oligocene. This volcanism form two main arcs: the older

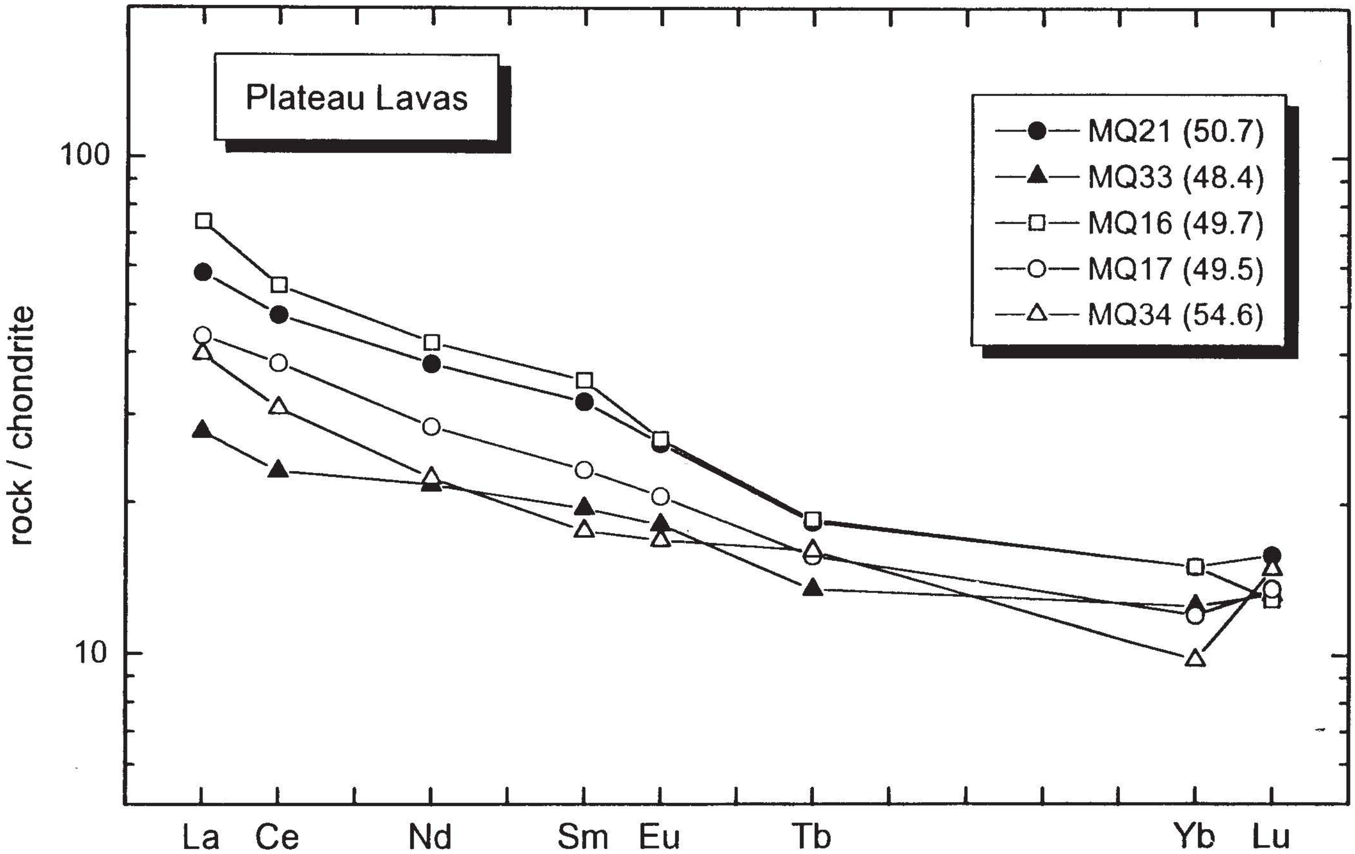

Fig. 7 - REE normalized diagram for selected plateau samples; in parentheses SiO_2 values are reported.

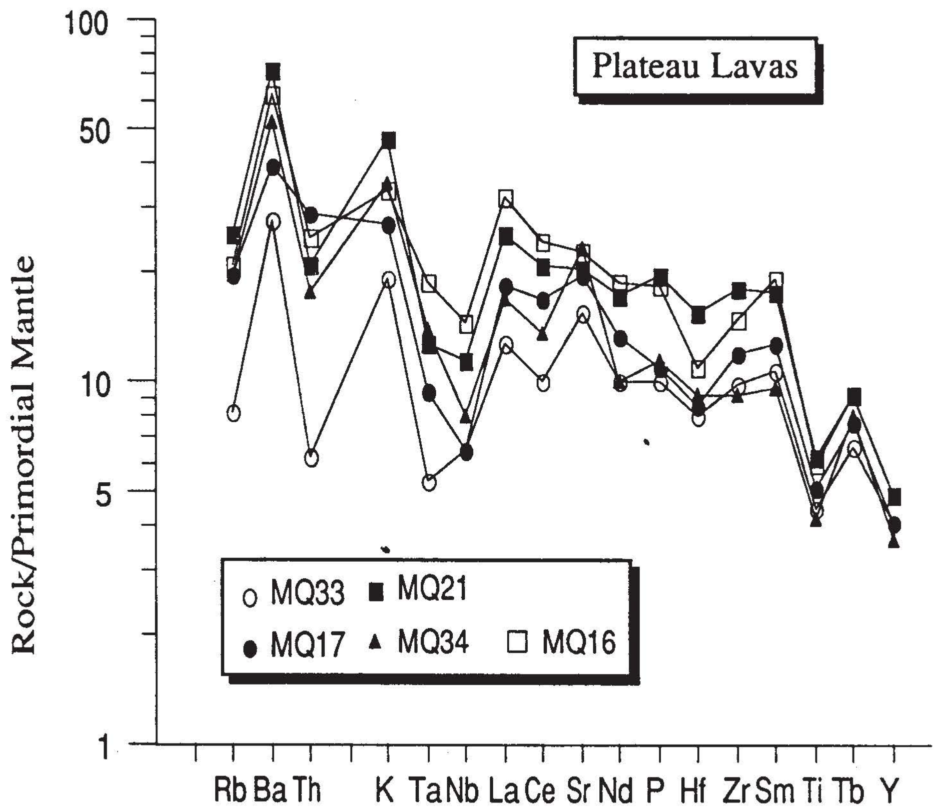

Fig. 8 - Spider diagrams for selected samples of basalts and basaltic andesites from RSMS-QMS plateau. Normalization values according to Wood (1979).

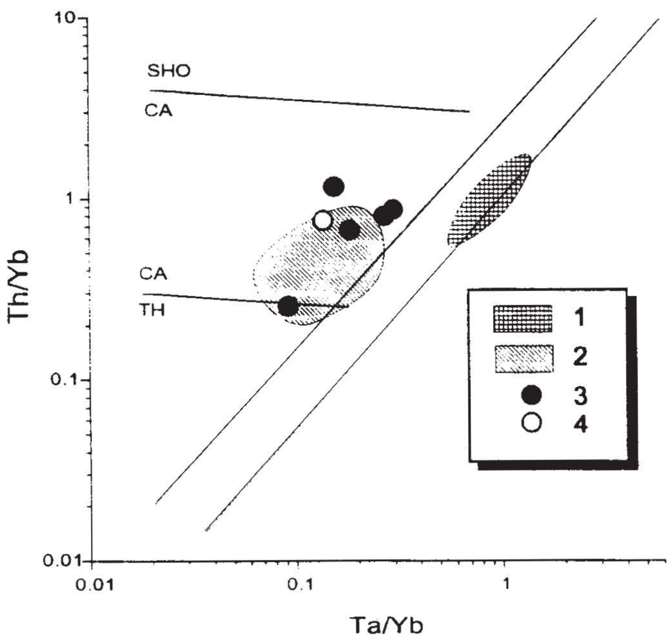

Fig.9. - Th/Yb vs. Ta/Yb discriminant diagram for orogenic and anorogenic basalts (Pearce, 1982). 1) Alkaline basalts from the western MVB; 2) Calcalkaline MVB basalts; 3) Plateau basalts; 4) Post-plateau basalts. Data from Luhr *et al.* (1989), Verma and Nelson (1989), and this work.

SMO and the younger and still active MVB. The transition between the two arcs is related to a reorganization of the Pacific convergent system in Miocene times (Karig *et al.*, 1978; Mammerickx and Klitgord, 1982; Stock and Hodges, 1989). On the continent this transition was marked by changes in tectonic style, in the composition and spatial distribution of volcanism (Ferrari *et al.*, this issue) and in the morphology of central Mexico. In this complex geologic framework the beginning of the MVB was characterized by scattered and diachronous andesitic volcanism developed mostly in continuity over the SMO sequence in the southern part of the present volcanic arc.

In this context the RSMS and QMS represent the first widespread and uniform volcanic event in the MVB history. The relatively primitive character of this volcanism implies the presence of an extensional state of stress in the lithosphere which allowed rapid uprising of the magma without significant differentiation episodes within the crust. This volcanism took place in the late-Miocene during the first pulse of the extensional phase that characterizes MVB volcanic activity. This extensional phase followed a phase of transcurrent and transtensional left-lateral tectonics (Pasquarè *et al.*, 1988) which probably coincided with the onset of MVB activity (Ferrari *et al.*, this issue).

Preliminary field investigations and other publications suggest the possible prolongation of this volcanism to the west in the Tepic area (Gastil *et al.*, 1979), and to the east near the Gulf of Mexico (López-Infanzón, 1990). Consequently this event would have an even greater importance since it would have developed over all the different structural provinces that constitute the present MVB. Therefore we consider this volcanism as the first unifying episode marking the developing of the MVB.

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