Geof. Int., Vol. 26-1, 1987, pp.109-158.

K-Ar AND GEOLOGIC DATA BEARING ON THE AGE AND EVOLUTION OF THE TRANS-MEXICAN VOLCANIC BELT

G. T. NIXON* **
A. DEMANT***
R. L. ARMSTRONG*
J. E. HARAKAL*

RESUMEN

Las fechas K-Ar recientemente obtenidas y publicadas y los mapas geológicos de las partes central y occidental del Cinturón Volcánico Mexicano (CVM) proporcionan una base para examinar la evolución del volcanismo del Cenozoico Tardío en la parte central de México. El arco volcánico moderno, compuesto principalmente de andesita y dacita calci-alcalinas, se formó durante el Cuaternario y su desarrollo está íntimamente conectado con los regímenes contrastantes de subducción de la placa Rivera y la parte norte de la Cocos. Los centros andesíticos mayores en la parte occidental del CVM que yacen sobre la porción subducida de la placa Rivera empezaron a evolucionar entre 0.6 y 0.2 Ma. Sin embargo, en las partes central y oriental del arco, donde está teniendo lugar la subducción de la placa Cocos, la edificación de los conos andesíticos-dacíticos comenzó considerablemente más temprano, aproximadamente 1.7 Ma. La anchura del arco activo por encima de la placa Cocos subducida ha disminuido apreciablemente durante el Cuaternario, de tal manera que el volcanismo andesítico se concentra en la actualidad más cerca de la trinchera. La temprana extinción del volcanismo en la región posterior del arco explica por qué los volcanes históricamente activos se encuentran comúnmente en el frente volcánico y por qué son ellos los que proporcionan un registro más completo del volcanismo Cuaternario. Sus grandes volúmenes son una consecuencia directa de su longevidad. Las tasas promedio de erupción para los conos cuaternarios mayores se estiman en 0.2 - 0.3 km^3/ka y no parecen particularmente sensibles a las diferencias en la tasa de subducción. El desarrollo de un sistema de arco calci-alcalino de rumbo E-W en la parte central de México data probablemente del Mioceno Tardío o del Plioceno Temprano. Desde entonces el volcanismo de arco ha migrado hacia la trinchera, llegando a su posición actual hacia la época Cuaternaria Temprana. Las rocas lamprofíricas ricas en K del Plioceno Temprano al Reciente, que afloran en la fosa de Colima, presentan patrones espacio-tiempo correlativos a los deducidos del volcanismo calci-alcalino contemporáneo y señalan a la subducción como el mecanismo causante común a ambos. El fisuramiento del Plioceno Temprano y la actividad lamprofírica en la fosa de Colima están eslabonados a las etapas tempranas de la formación de una frontera de transformación separando las placas Rivera y Cocos. Al presente, esta transformación sísmicamente activa continúa a su subducción por debajo de la fosa de Colima. Las secuencias sódicas alcalinas en la parte más occidental del CVM pueden representar volcanismo de la región posterior del arco o relacionarse con fenómenos poco entendidos que ocurren en la terminación de las zonas de subducción.

* *Department of Geological Sciences, University of British Columbia, Vancouver, British Columbia, Canada V6T 2B4*

** *Present address: Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada K7L 3N6.*

*** *Laboratoire de Petrologie, Faculté des Sciences et Techniques de Saint-Jérôme, Université d'Aix-Marseille III, 13397 Marseille, CEDEX 13, France.*

ABSTRACT

New and published K-Ar dates and geologic mapping in the western and central parts of the Trans-Mexican Volcanic Belt (TMVB) provide a basis for examining the evolution of Late Cenozoic volcanism in Central Mexico. The modern volcanic arc, composed principally of calc-alkaline andesite and dacite, was formed during the Quaternary and its development is intimately connected with the contrasting subduction regimes of the Rivera and northern Cocos plates. Major andesitic centers in the western TMVB that lie above the subducted portion of the Rivera plate began to evolve between 0.6 and 0.2 Ma. However, in the central and eastern parts of the arc where subduction of the Cocos plate is taking place, the construction of andesite-dacite cones started considerably earlier at approximately 1.7 Ma. The width of active arc above the subducted Cocos plate has decreased appreciably during the Quaternary such that andesitic volcanism is currently focused nearest the trench. The early extinction of volcanism in the backarc region explains why historically active volcanoes are commonly found at the volcanic front and why they generally provide a more complete record of Quaternary volcanism. Their large volumes are a direct consequence of their longevity. The average eruption rates for major Quaternary cones are estimated at 0.2 - 0.3 km^3/ka and do not appear particularly sensitive to differences in the rate of subduction. The development of an E-W - trending calc-alkaline arc system in Central Mexico probably dates back to Late Miocene or Early Pliocene. Arc volcanism since that time has migrated trenchward arriving at its present position by Early Quaternary time. Exposures of Early Pliocene to Recent K-rich lamprophyres in the Colima graben exhibit space-time patterns correlative with those deduced for coeval calc-alkaline volcanism and point to subduction as the common causative mechanism. Early Pliocene rifting and lamprophyric activity in the Colima graben are linked to the early stages of formation of a transform boundary separating the Cocos and Rivera plates. Today, this seismically active transform continues to be subducted beneath the Colima graben. Sodic alkaline suites in the westernmost part of the TMVB may represent backarc volcanism or be related to poorly understood phenomena occurring at the termination of subduction zones.

INTRODUCTION

The locus of Late Cenozoic volcanism in Central Mexico, commonly referred to as the Trans-Mexican Volcanic Belt (TMVB), traverses the continent in an E-W direction between the 19th and 21st parallels. The volcanic arc is superposed on the prominent NNW-SSE structural grain of Mexico crossing Oligocene-Miocene ignimbrites and associated rocks of the Sierra Madre Occidental, the Mesozoic fold belt of the Sierra Madre Oriental, overthrust terranes of the Cordilleran system, and Palaeozoic basement rocks exposed in eastern Mexico (Fig. 1).

The majority of recent workers have related the E-W orientation of TMVB volcanism to northeasterly subduction of ocean lithosphere beneath Mexico along the Middle America Trench (Demant, 1978, 1981; Aubouin *et al.*, 1982; Nixon, 1982; Burbach *et al.*, 1984; Luhr *et al.*, 1985). Alternative tectonic interpretations are summarized by Verma (1985). Nixon (1982) divided the Quaternary arc into two structurally distinct segments: a narrow western arc associated with subduction of the young Rivera plate that completely lacks Benioff-Zone seismicity; and a much broader central and eastern arc related to subduction of the northern Cocos plate.

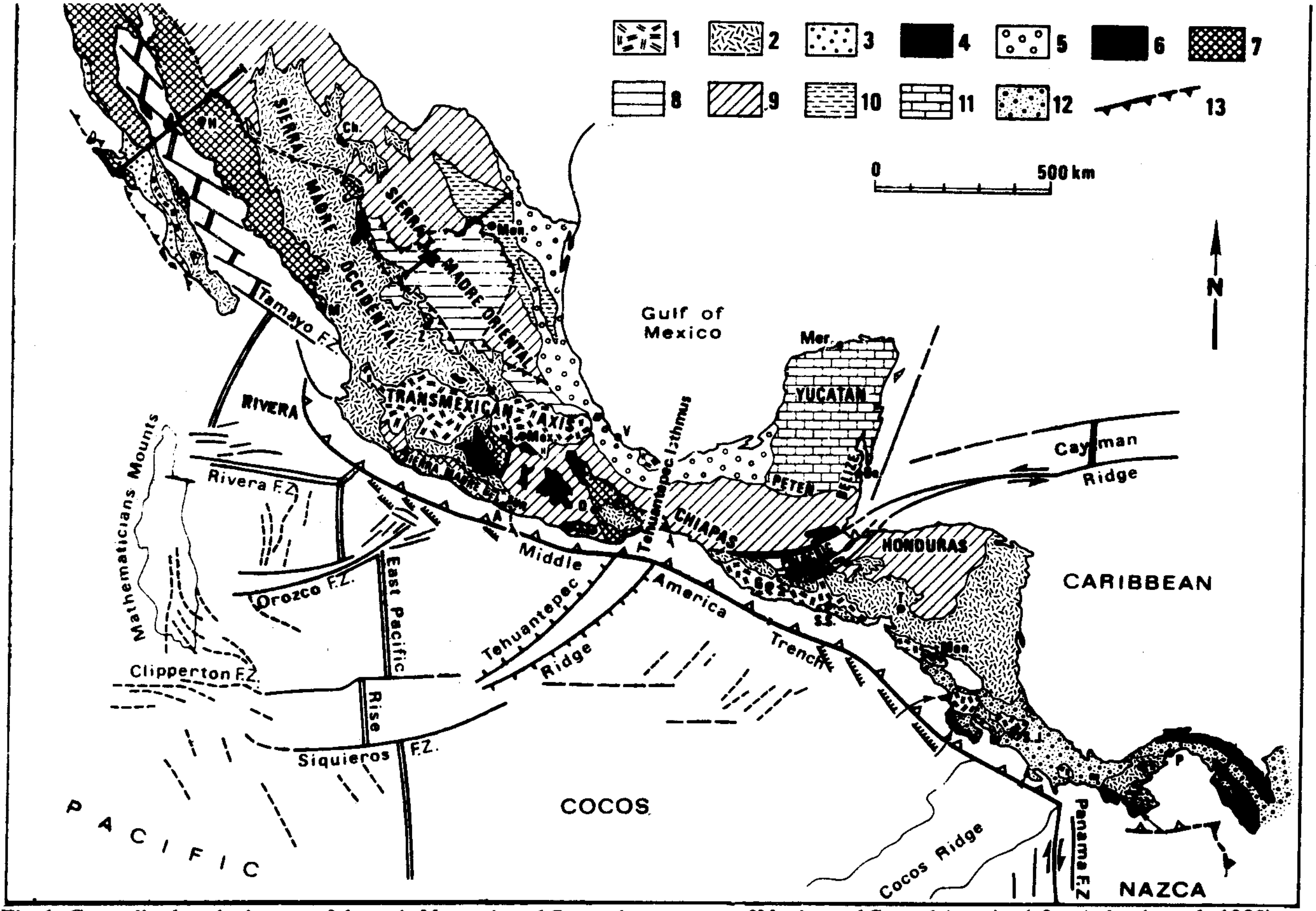

Fig. 1. Generalized geologic map of the main Mesozoic and Cenozoic structures of Mexico and Central America (after Aubouin *et al.*, 1982). *Volcanic rocks:* 1) Plio-Quaternary; 2) Oligocene-Miocene; *Molasse:* 3) Marine, Cretaceous to Cenozoic (Baja California); 4) Continental, Eocene to Miocene (Mexican Altiplano and regions south of the TMVB); 5) Marine, Eocene to Miocene (Gulf of Mexico Coastal Plains); 6) *Oceanic Mesozoic complexes;* 7) *Volcaniclastic rocks,* Triassic and Early Cretaceous; *Sierra Madre Oriental* system; 8) Allochthonous terranes; 9) Autochthonous platform with Palaeozoic basement (including Precambrian rocks near Oaxaca); 10) *Sabinas Basin;* 11) *Cenozoic platform of the Yucatan;* 12) *Cenozoic formations of Central America;* 13) Main overthrusts.

The boundary between these segments is marked by a N-S - trending structural depression known as the Colima graben which coincides with a 100 km offset in the trenchward limit of arc volcanism (Fig. 2). The Colima graben overlies a NE-SW-striking sinistral transform fault in the subducted slab that originates at the intersection of the East Pacific Rise and the eastern end of the Rivera Fracture Zone. This seismically active zone of transform faulting defines the boundary between the Rivera plate with a relatively slow subduction rate (2 cm/yr) and the more rapidly subducting Cocos plate (6-8 cm/yr) to the east.

The more recent volcanoes of the TMVB may be divided into three morphological categories:

1) The major central volcanoes are exclusively calc-alkaline and composed primarily of orogenic andesite and dacite in the sense of Gill (1981). These polygenetic cones may define the trenchward limit of arc volcanism (e.g. Volcán de Colima, Popocatépetl, and Pico de Orizaba), or lie just behind monogenetic cones and flows that locally occupy the 'volcanic front' (e.g. Nevado de Toluca and La Malinche), or form N-S lineaments within the overall E-W trend of the TMVB (the most notable are Orizaba - Cofre de Perote, Popocatépetl - Iztaccíhuatl, and the Colima volcanoes; Fig. 2). In common with other circum-Pacific arcs, all of the large historically active volcanoes occur at the 'volcanic front'.

2) Monogenetic volcanoes and associated flows with total volumes of the order of 1 km^3 occur throughout the TMVB, locally to the exclusion of the major cones (e.g. immediately east of the Colima graben in Michoacán). Although the vast majority of these volcanoes are calc-alkaline with the total range of volcanic products varying from basalt to rhyolite, mafic alkaline variants of sodic or potassic affinity are becoming increasingly better known (Luhr and Carmichael, 1985). To date most of the alkaline rocks have been reported from the Colima graben and the western extremity of the TMVB (Luhr *et al.*, 1985).

3) large caldera-and-dome complexes are much less common among the products of recent volcanism than volcanoes in categories 1 and 2. These complexes are rhyolitic and either mildly peralkaline (e.g. Sierra La Primavera, Mahood, 1980) or calc-alkaline (e.g. Los Azufres, Demant, 1981), or form shield volcanoes comprising basaltic to andesitic lavas and rhyolitic ignimbrites (e.g. Los Humeros, Demant, 1981; Ferriz, 1985). They do not appear to be restricted to any particular part of the TMVB (Fig. 2).

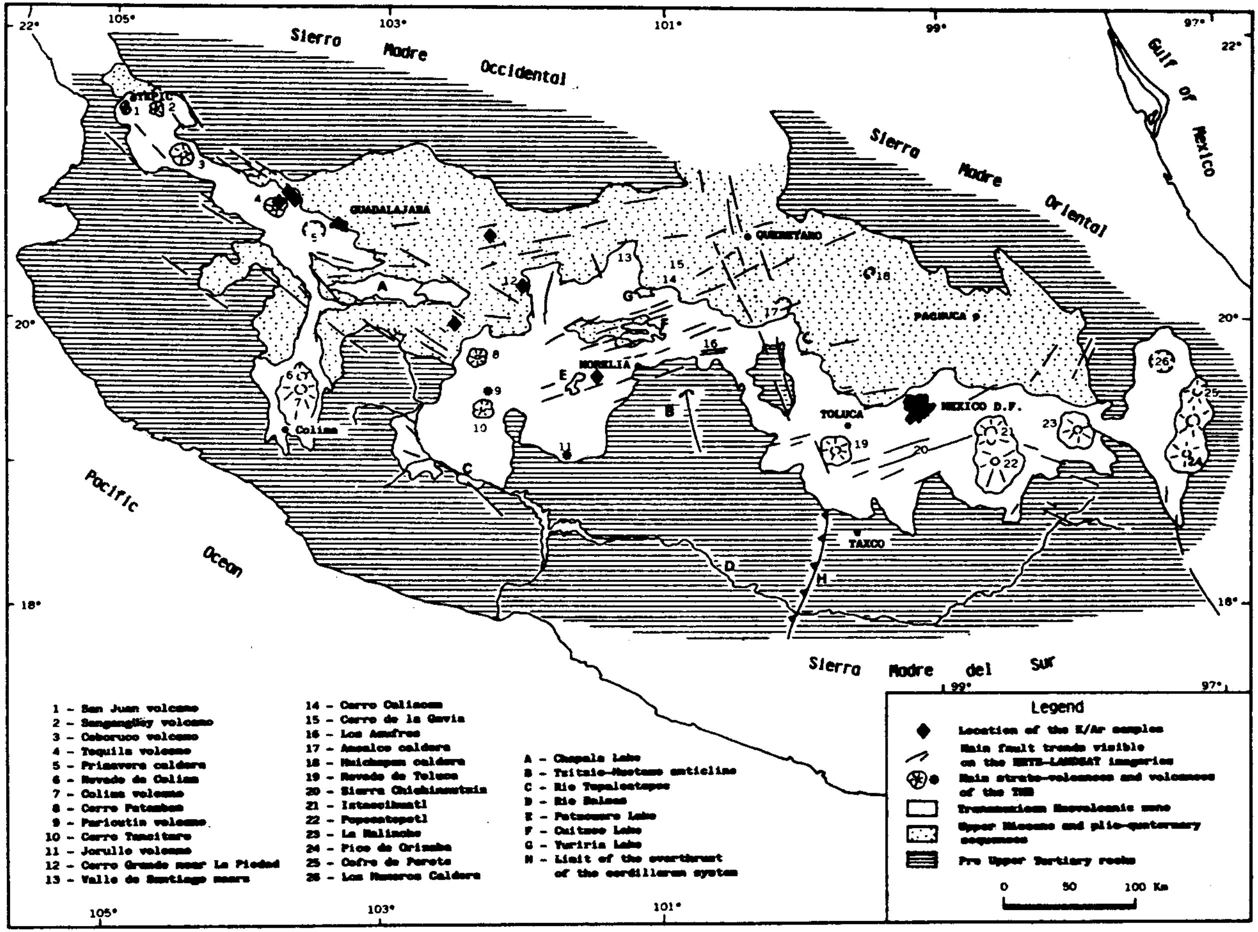

Fig. 2. Generalized map of the Trans-Mexican Volcanic Belt showing locations of K-Ar dates presented in Table 2 (after Demant, 1981).

Despite the coeval eruption of alkaline and calc-alkaline suites in parts of the TMVB, calc-alkaline rocks and in particular andesites and dacites are volumetrically most important. This fact must be given prime consideration in tectonic hypotheses dealing with their common origin.

The age for the onset of volcanism with an overall E-W trend in Central Mexico is not at all clear from published literature. For example, Gastil *et al.* (1979) dealing with the western extremity of the volcanic arc placed the earliest volcanism in the TMVB at approximately 4.5 Ma. In eastern Mexico, Cantagrel and Robin (1979) established three distinct cycles of volcanic activity beginning at 20 Ma; the most recent or 'Neovolcanic' cycle commencing at about 3 Ma. In the Valley of Mexico, Mooser *et al.* (1974) combined K-Ar and palaeomagnetic data to construct seven phases of volcanism beginning in the Oligocene (30 Ma). In particular, the work of Mooser and his colleagues (Gunn and Mooser, 1970; Mooser, 1972; Mooser *et al.*, 1974) has been notably influential in establishing a chronology for the TMVB (Bloomfield and Valastro, 1974, 1977; Erffa and Hilger, 1975; Richter and Negendank, 1976; Urrutia and Pal, 1977; Martin del Pozzo, 1982). Such grossly discrepant estimates for the inception of volcanism in geographically remote areas are partly a problem of semantics and how best to define TMVB volcanism at any single locale given the limited data at hand; but difficulties also arise because of the collage of older volcanic terranes crossed by the modern volcanic arc. In fact, as we show below, these complexities are part of the dynamic nature of Cordilleran arc magmatism in time and space (Demant and Robin, 1975; Demant, 1978; Damon *et al.*, 1981; Clark *et al.*, 1982).

In this publication we combine our own geologic mapping in the central and western parts of the TMVB with both new and previously published isotopic dates in order to develop a working chronology for the TMVB as a whole. A compilation of published K-Ar dates for rocks *spatially* associated with the TMVB is given in Table 1 which includes recent data for the Colima graben (Allan, in press), and Iztaccíhuatl (Nixon *et al.*, in prep.). A supplementary compilation of K-Ar dates is given by Vinegas *et al.* (1985). In addition, the results of seven new K-Ar age determinations on volcanic rocks from the central and western parts of the TMVB are presented in Table 2. Chemical analyses of the latter samples are given in the Appendix; analytical methods are those of Armstrong and Nixon (1980). For descriptive purposes, we divide the TMVB into geographic regions which are treated sequentially below from west to east. The term TMVB is most clearly used to denote the E-W oriented 'chain' of recently active volcanoes that are predominantly calc-alkal-

TABLE 1: Compilation of K-Ar Dates for Late Cenozoic Volcanic Rocks Associated with the Trans-Mexican Volcanic Belt.

Sample No.	Latitude (N)	Longitude (W)	Rock Type	Material dated	K-Ar Date (Ma) ±1σ error	Ref.+
WESTERN TRANS-MEXICAN VOLCANIC BELT						
1. Tepic Region						
1a. Early Miocene						
246	21°18´50"	104°36´35"	rhyolite	Plag	21.3 ± 0.9	1
393	21°22´55"	104°58´50"	andesite	Plag	20.4 ± 2.9	1
165	21°12´15"	105°04´50"	rhyolite	Plag	18.5 ± 0.7	1
404	21°15´10"	104°55´27"	rhyolite	Sa	18.1 ± 0.8	1
369	21°19´00"	105°00´15"	basalt	Plag	16.0 ± 0.7	1
1b. Middle to Late Miocene						
188	21°12´25"	104°54´50"	basalt	Plag	13.8 ± 3.0	1
1155	20°55´00"	105°32´00"	welded tuff	Sa	11.1 ± 0.2	2
1151	20°47´10"	105°30´25"	basalt	Plag	10.2 ± 0.8	2
1150	20°57´00"	105°22´55"	basalt	Plag	10.1 ± 0.3	2
193	21°41´20"	105°05´40"	basalt	WR	9.9 ± 0.3	1
1152	21°01´45"	105°16´40"	basalt	Plag	8.3 ± 0.6	2
421	21°43´25"	105°02´10"	rhyolite	Sa	7.8 ± 0.6	1
1c. Plio-Quaternary						
284	21°19´45"	104°34´25"	rhyolite	Sa	4.6 ± 0.2	1
231	21°27´20"	104°32´15"	basalt	Plag	4.3 ± 1.7	1
267	21°09´50"	104°46´30"	rhyolite	Plag	2.3 ± 0.5	1
343	21°09´45"	104°52´00"	andesite	Plag	2.3 ± 2.2	1
439	21°27´05"	105°05´40"	andesite	Plag	2.1 ± 0.4	1
204	21°31´15"	104°43´30"	rhyolite	Hb	1.6 ± 2.5	1
204	21°31´15"	104°43´30"	rhyolite	Sa	1.5 ± 2.3	1
143	21°30´30"	105°04´15"	dacite	Plag	1.2 ± 1.5	1
1d. Quaternary						
269	21°10´00"	104°45´00"	dacite	Plag	0.16 ± 0.5	1
2. Tequila Region (Cerro Saavedra and Volcán de Tequila) -- Quaternary						
-	20°54´00"	103°52´00"	obsidian	An	0.55 ± 0.04	3
-	20°47´00"	103°50´30"	andesite	WR	0.21 ± 0.01	3
3. Guadalajara Region						
3a. Rio Grande de Santiago -- Late Miocene						
1	20°51´00"	103°19´59"	basalt	WR	9.5 ± 0.1	4
2	20°51´10"	103°20´00"	basalt	WR	9.2 ± 0.1	4
3	20°50´50"	103°19´55"	rhyolitic tuff	WR	9.1 ± 0.1	4
4	20°49´02"	103°20´20"	basalt	WR	9.0 ± 0.2	4
3b. Rio Grande de Santiago -- Pliocene						
5	20°48´20"	103°30´30"	andesite	WR	5.5 ± 0.1	4
6	20°46´25"	103°20´25"	ignimbrite	WR	4.8 ± 0.1	4
7	20°46´20"	103°20´20"	basalt	WR	4.7 ± 0.1	4
65-4	20°43´55"	103°20´05"	ignimbrite	WR	3.5 ± 0.1	5

(Cont. Tab. 1)

3c. Sierra La Primavera -- Quaternary

193	20°40´40"	103°35´30"	rhyolite	Sa	0.15 ± 0.02	6
317	20°40´00"	103°31´00"	rhyolite	Sa	0.11 ± 0.01	6
133	20°37´30"	103°31´30"	rhyolite	Sa	0.10 ± 0.01	6
25	20°37´30"	103°30´00"	rhyolite	Sa	0.07 ± 0.01	6
15	20°39´45"	103°28´00"	rhyolite	WR	0.03 ± 0.01	6

4. Zacoalco Region (50 km SSW of Guadalajara) -- Pliocene to Quaternary

C78	20°12´00"	103°33´00"	Hb andesite	Hb	5.2 ± 0.4	7
C69	20°13´30"	103°35´30"	andesite	WR	4.6 ± 0.1	7
B13	20°21´00"	103°32´30"	dacite	WR	1.44 ± 0.02	7
C148	20°21´00"	103°32´00"	HK andesite	WR	1.3 ± 0.1	7
M211A	20°22´00"	103°33´30"	andesite	WR	0.99 ± 0.01	7
A27	20°25´00"	103°35´00"	HK andesite	WR	0.65 ± 0.1	7

5. Colima Graben - Late Miocene to Quaternary

M203A	20°04´30"	103°27´30"	andesite	WR	10.1 ± 0.4	7
C85	20°05´00"	103°35´30"	Hb andesite	Hb	5.4 ± 0.2	7
A120	20°00´30"	103°32´30"	andesite	WR	4.96 ± 0.03	7
M197	20°04´00"	103°36´30"	andesite	WR	4.89 ± 0.03	7
B116	19°52´30"	103°39´00"	Ph-Ka ankaratrite	Ph	4.69 ± 0.05	7
A111	20°03´00"	103°37´30"	basalt	WR	4.65 ± 0.05	7
C91	20°05´00"	103°35´30"	Hb HK andesite	WR	4.56 ± 0.04	7
505	19°50´00"	103°37´00"	Hb-Bi dacite	Hb	4.56 ± 0.01	7
A45	20°07´30"	103°33´30"	Hb lamprophyre	WR	4.42 ± 0.03	7
C13	20°05´00"	103°35´30"	Ol andesite	WR	4.35 ± 0.06	7
A138	19°50´00"	103°37´00"	Ph lamprophyre	Gmass	4.28 ± 0.02	7
B60	19°42´00"	103°24´00"	Ph lamprophyre	Ph	4.23 ± 0.03	7
C141	19°54´00"	103°38´30"	Ph lamprophyre	Ph	4.21 ± 0.07	7
C145	19°54´00"	103°38´30"	Ph-Hb lamprophyre	Ph+WR	4.2 ± 0.1	7
A60	20°03´30"	103°25´30"	Hb lamprophyre	WR	4.16 ± 0.04	7
C140	19°54´00"	103°38´30"	Ph lamprophyre	WR	4.20 ± 0.03	7
B69	19°56´00"	103°42´00"	Ph-Hb lamprophyre	WR	3.29 ± 0.02	7
A89	19°54´30"	103°28´30"	Hb HK andesite	WR	2.41 ± 0.04	7
M169	19°49´30"	103°36´00"	Bi-Hb dacite	Hb	1.7 ± 0.1	7
B44	19°47´00"	103°27´30"	Hb lamprophyre	WR	1.26 ± 0.02	7
A4	19°51´00"	103°31´00"	Hb lamprophyre	WR	1.15 ± 0.04	7
B31	19°49´30"	103°37´30"	Hb HK andesite	WR	0.58 ± 0.02	7

6. Cantaro Volcanic Complex(northeastern margin of Colima Graben) -- Quaternary

M231	19°43´00"	103°37´00"	Bi-Hb dacite	Bi+Hb	1.4 ± 0.1	7
M238	19°39´30"	103°40´30"	Bi-Hb andesite	Plag	0.95 ± 0.1	7

7. Nevado de Colima and Volcán de Colima -- Quaternary

Co-119	19°36´05"	103°40´30"	andesite	WR	0.53 ± 0.1	8
Co-70	19°37´10"	103°40´30"	andesite	WR	0.37 ± 0.05	8
Co-56	19°35´20"	103°30´40"	andesite	WR	0.29 ± 0.08	8
Co-45	19°35´30"	103°35´40"	andesite	WR	0.14 ± 0.04	8
Co-113	19°31´40"	103°26´30"	pyroclast	WR	0.08 ± 0.03	8

CENTRAL TRANS-MEXICAN VOLCANIC BELT

8. Michoacán (Los Azufres Region) -- Mid-Miocene and Quaternary

IS-23	19°39´00"	100°57´00"	andesite	WR	14.1 ± 0.7	9
443	19°53´40"	100°45´30"	rhyolite	WR	1.6 ± 0.15	9
455	19°47´30"	100°29´10"	rhyodacite	WR	0.36 ± 0.08	9
452	19°32´00"	100°23´50"	rhyodacite	WR	0.05 ± 0.03	9

(Cont. Tab. 1)

9. Nevado de Toluca -- Quaternary						
NE-20	18°53′00"	99°38′50"	andesite	WR	1.6 ± 0.15	10
VNE-5	19°09′00"	99°48′10"	andesite	WR	1.54 ± 0.07	10
NE-17	18°58′30"	99°38′50"	andesite	WR	1.3 ± 0.3	10
NE-19	18°57′30"	99°42′55"	andesite	WR	1.2 ± 0.1	10
10. Iztaccíhuatl(Sierra Nevada) -- Quaternary						
LG-4	19°13′30"	98°41′54"	dacite	WR	0.90 ± 0.07	11
LG-10	19°10′14"	98°44′44"	dacite	WR	0.58 ± 0.12	11
R-12	19°09′00"	98°40′01"	andesite	Plag	0.58 ± 0.11	11
P-6	19°08′19"	98°38′12"	dacite	Plag	0.41 ± 0.14	11
IZ-1	19°08′28"	98°38′32"	dacite	Plag	0.34 ± 0.09	11
IZ-620	19°07′32"	98°38′56"	andesite	WR	0.27 ± 0.02	11
IZ-254	19°11′40"	98°37′30"	dacite	WR	0.08 ± 0.02	11
EASTERN TRANS-MEXICAN VOLCANIC BELT						
11. Pachuca Region (Altiplano margin north and east of Pachuca) -- Mio-Pliocene						
VE118	19°47′00"	97°35′00"	andesite	WR	7.7 ± 0.3	12
PH62	20°38′00"	98°38′00"	basaltic andesite	WR	2.56 ± 0.08	12
PH40	20°23′00"	98°35′00"	basaltic andesite	WR	2.38 ± 0.08	12
12. La Malinche Region (50 km north at Tlaxco) -- Quaternary						
VE116	19°38′00"	98°07′00"	basaltic andesite	WR	1.50 ± 0.07	12
13. Cofre de Perote Region -- Quaternary						
VE66	19°23′00"	96°36′00"	transitional basalt	WR	1.90 ± 0.06	12
VE52	19°29′00"	96°48′00"	andesite	WR	1.57 ± 0.05	12
VE21	19°38′00"	97°08′00"	K-rich andesite	WR	0.47 ± 0.02	12

All K-Ar dates are standardized to the decay constants recommended by Steiger and Jäger (1977).

Abbreviations: Hb - hornblende; Plag - Plagioclase; Bi - biotite; An - anorthoclase; Ka - kalsilite; Ol - olivine; Sa - sanidine; WR - whole-rock; Gmass - groundmass.

+References:

1. Gastil et al. (1978) and Gastil et al. (1979)
2. Jensky (1975)
3. Harris and Carmichael, 1984; J. Harris, pers. comm., 1984
4. Watkins et al. (1971)
5. Mahood (1977)
6. Mahood and Drake (1982); 5 representative dates chosen from 46 reported dates.
7. Allan (in press)
8. Robin et al. (1984)
9. Demant et al. (1975)
10. Cantagrel et al. (1981)
11. Nixon et al. (in prep.)
12. Cantagrel and Robin (1979)

Table 2: New K-Ar Age Determinations for Late Cenozoic Lavas Associated with the Trans-Mexican Volcanic Belt

No.	Sample	Volcanic Unit	Latitude (N)	Longitude (W)	Material[1] dated	%K[2]	$^{40}Ar^*$(x10^{-10} mol/gm)	%$^{40}Ar^*$	Date ±1σ error
Western Trans-Mexican Volcanic Belt — Tequila Region									
1	506	Volcán de Tequila	20°48′30"	103°50′50"	WR	2.17	0.00847	9.3	0.22±0.03
2	624	San Martin	20°55′34"	103°50′50"	WR	3.77	0.04104	48.4	0.63±0.03
3	634	Mesa Santa Rosa	20°54′05"	103°43′50"	WR	1.01	0.01623	21.7	0.93±0.05
Central Trans-Mexican Volcanic Belt — Eastern Jalisco (Arandas Region) and Northern Michoacán									
4	340	Cerro Sanambo	19°37′43"	101°25′45"	WR	1.49	0.0225	24.0	0.87±0.05
5	706	Cerro Grande La Piedad	20°15′20"	102°03′30"	WR	0.98	0.0272	16.4	1.60±0.10
6	881	Cerro Alto	19°59′45"	102°28′30"	WR	1.05	0.0480	30.5	2.60±0.10
7	1131	Arandas basalt flow	20°42′00"	102°19′15"	WR	1.14	0.2018	58.4	10.20±0.30

[1] The size fraction of material dated was -30+40 mesh.
[2] Average value of replicate analyses determined by atomic absorption and XRF techniques.
σ = one standard deviation; WR = whole-rock; $^{40}Ar^*$ = radiogenic ^{40}Ar
Constants used: $^{40}K\lambda_\beta$ = 4.962x10^{-10} yr^{-1}; $^{40}K\lambda_e$ = 0.581x10^{-10} yr^{-1}; $^{40}K/K$ = 0.01167 atom %

1. 506: Andesite flow on the upper flanks of Volcán de Tequila. Phenocrysts of plagioclase, hypersthene, and augite set in a glassy groundmass containing microlites of plagioclase, clinopyroxene, orthopyroxene, and opaque oxides.
2. 624: Dacite flow of San Martin de Las Cañas. Sparse phenocrysts of plagioclase and augite and opaque microphenocryst in pale brown glass.
3. 634: Ophitic-textured basalt flow capping the Mesa Santa Rosa. Microphenocrysts of plagioclase, olivine, augite and opaque oxides.
4. 340: Andesite flow on the flank of Cerro Sanambo. Phenocrysts of plagioclase, augite, and hypersthene contained in a microlitic groundmass with dark brown glass.
5. 706: Basaltic flow at the base of Cerro Grande. Sparse phenocrysts of olivine and plagioclase enclosed in a microlitic groundmass comprising plagioclase, olivine, augite, opaques, and dark brown glass.
6. 881: Margin of Cerro Alto andesite dome. Abundant phenocrysts of plagioclase and hornblende with minor hypersthene and opaques set in a fine-grained groundmass.
7. 1131: Basaltic flow capping the plateau 2 km east of Arandas. Phenocrysts of olivine and plagioclase set in a subophitic groundmass of plagioclase, augite, and opaque oxides.

ine in composition. The large volume cones of calc-alkaline andesite and dacite are especially important since many of these have been historically active (Mooser *et al.*, 1958) and provide a first-order link with the present subduction regime (Nixon, 1982). More importantly for the purpose at hand, these volcanoes are long-lived and exhibit complex growth histories, which renders them ideal candidates for establishing the age of the last major phase of calc-alkaline volcanism of E-W orientation (*i.e.* TMVB as adopted above) and enables us to compare the evolution of volcanism at points along the arc.

APPENDIX

Chemical Analyses of Samples Dated by K-Ar Methods

	1	2	3	4	5	6	7
Sample No.	506	624	634	340	706	881	1131
SiO_2	61.80	68.18	49.42	60.38	51.98	60.19	51.30
TiO_2	0.83	0.53	2.39	0.80	1.44	0.81	1.40
Al_2O_3	16.07	15.20	15.75	17.42	17.66	16.99	15.96
Fe_2O_3	2.47	0.82	3.27	2.18	2.67	2.14	4.71
FeO	3.45	2.31	8.43	3.72	5.43	3.03	6.03
MnO	0.13	0.10	0.19	0.05	0.10	0.06	0.18
MgO	2.18	0.54	5.93	3.18	5.53	3.22	5.35
CaO	5.22	1.30	8.93	6.18	7.98	6.88	9.20
Na_2O	3.92	5.53	3.71	3.72	3.51	4.07	3.07
K_2O	2.49	4.73	1.17	1.63	1.28	1.31	1.58
P_2O_5	0.16	0.12	0.67	0.26	0.34	0.22	0.33
H_2O^+	1.46	0.25	0.27	0.48	1.44	0.06	0.01
H_2O^-	0.10	0.01	0.08	0.08	0.23	0.09	0.12
Total	100.28	99.62	100.21	100.08	99.59	99.07	99.23

Major element analyses were performed by atomic absorption spectrophotometry (analyses 2-7) at U.S.T.L., Montpellier, France (Demant, 1981) and by X-ray fluorescence spectrophotometry (analysis 1) except FeO which was determined by titration and H_2O^+ and H_2O^- which were analyzed gravimetrically at 900°C and 120°C respectively. Na_2O in analysis 1 was determined on a pressed powder pellet (see Armstrong and Nixon (1980) for analytical details).

THE WESTERN PART OF THE TMVB

The western part of the TMVB can be subdivided into three main structural regions: 1) the Tepic-Chapala graben trending NW-SE; 2) the Guadalajara region located at the intersection of the Tepic-Chapala and Colima grabens; and 3) the Colima graben which has a N-S orientation.

1) *The Tepic-Chapala Graben*

The western end of the TMVB extends from Guadalajara to the Pacific coast and lies within a topographic depression known as the Tepic-Chapala graben (Demant, 1976, 1979; Fig. 2). Quaternary lavas and pyroclastic rocks commonly occupy elongate NW-SE or E-W oriented basins within Tertiary volcanic rocks. Although mappable faults are scarce, the margins of these basins are sharply defined and appear to be largely controlled by pre-Quaternary faults. These structures together with the NW-SE alignment of scoria cones on the flanks of composite volcanoes such as Sangangüey, Ceboruco, and Volcán de Tequila, clearly underscore the presence of NW-SE trending fractures in the basement rocks. Previously published work in this part of the TMVB has focused on the geology and geochemistry of major andesitic centers such as Volcán Ceboruco (Thorpe and Francis, 1975; Nelson, 1980), caldera complexes such as Sierra La Primavera (Mahood, 1977, 1980, 1981), and the petrology of parasitic cones on the flanks of Sangangüey (Nelson and Carmichael, 1984). With the exception of Sierra La Primavera, isotopic calibration of the growth histories of major volcanoes is currently lacking. K-Ar dates published by Gastil *et al.* (1978, 1979) primarily concern Late Tertiary volcanic stratigraphy and most of their youngest dates have rather large analytical uncertainties (Table 1). Our new K-Ar dates for Quaternary lavas in the Tequila region document more precisely the development of major andesitic volcanoes in this part of the TMVB.

1a) *The Tepic Region*

A geological reconnaissance map of the Tepic area published by Gastil *et al.* (1978) is reproduced in Figure 3 with minor modifications by Demant (1981). Based on geologic mapping and K-Ar dating (Table 1), Gastil *et al.* (1978, 1979) recognized three main volcanic sequences: 1) a Miocene sequence (21 - 16 Ma) composed mainly of rhyolites with associated andesites and basalts; 2) a Late Miocene sequence (11 - 8 Ma excluding one date with a large analytical uncertainty) consisting predominantly of basalts with thin interbedded ashflow tuffs that is exposed near the Pacific coast and between Tepic and El Jigote (Fig. 3); and 3) Plio-Quaternary volcanic

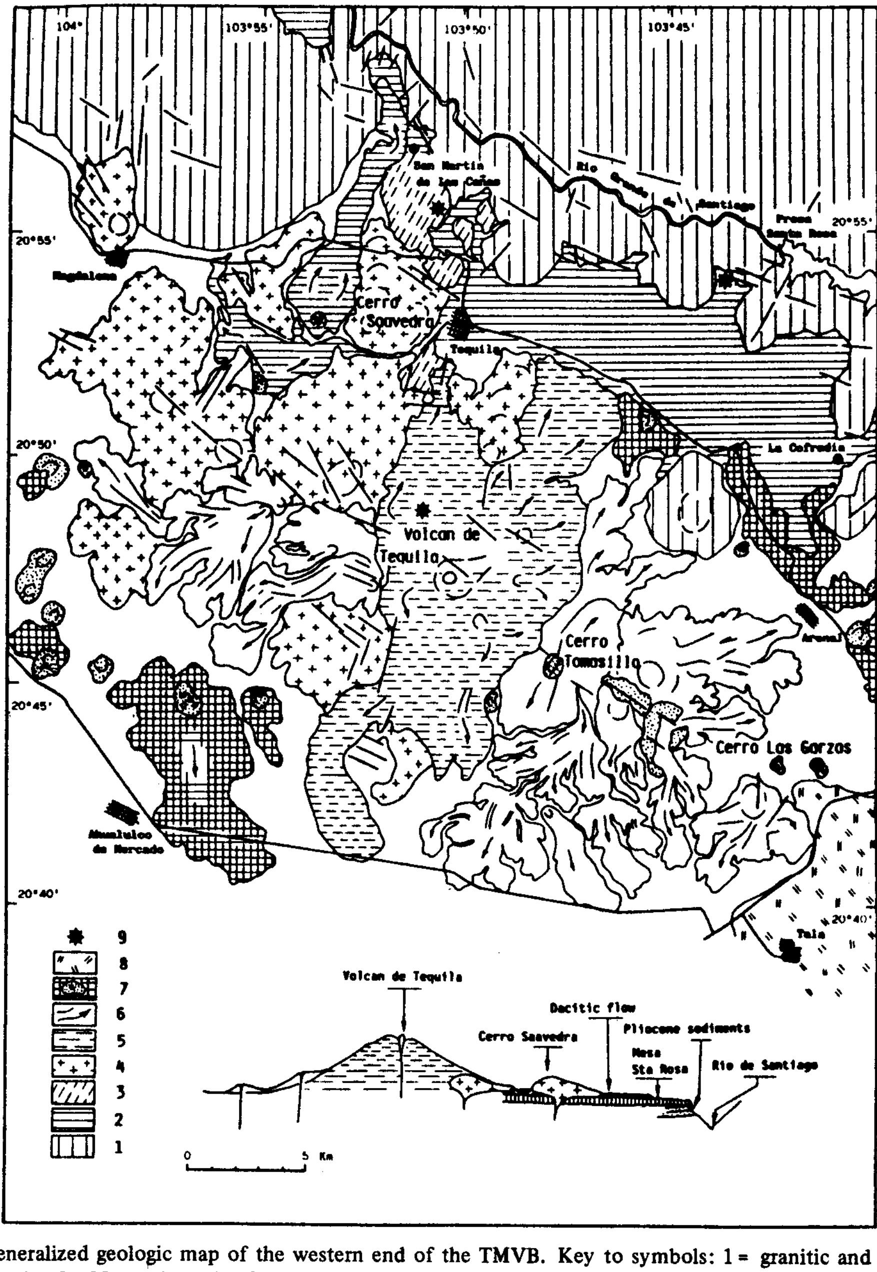

Fig. 3. Generalized geologic map of the western end of the TMVB. Key to symbols: 1 = granitic and gabbroic intrusive rocks; 2 = Mesozoic rocks; 3 = Miocene volcanic rocks; 4 = Late Miocene volcanic rocks (mainly basalts); 5 = Plio-Quaternary volcanic rocks (asterisks indicate source vents); 6 = Quaternary volcanic rocks of the TMVB (circles indicate small cinder cones); 7 = coastal mangrove swamps.

rocks (<5 Ma) comprising basalts, andesites, dacites, and rhyolites. Included in this group are Early Pliocene rhyolites of Santa María del Oro (4.6 Ma) and recently active andesitic volcanoes such as Volcán San Juan (Luhr, 1978) and Ceboruco (Thorpe and Francis, 1975; Nelson, 1980; Demant, 1981).

The chronology of Tertiary volcanic rocks in this part of the TMVB is closely linked with the magmatic and tectonic evolution of the Pacific margin of Mexico. Firstly, the oldest volcanic rocks recognized in the Tepic region are Miocene (21 - 16 Ma) and significantly younger than the predominantly Oligocene volcanic assemblages that compose most of the Sierra Madre Occidental such as the 35 - 23 Ma ignimbrite sequences in the Mazatlán-Durango transect (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979). During the Middle to Late Tertiary a progressive change in the locus and nature of magmatic activity is apparent. Calc-alkaline volcanism shifted westward from the eastern margin of the Sierra Madre Occidental to the Pacific coastal region by Early Miocene, possibly in response to a change in convergence rate between the Farallon and North American plates (McDowell and Clabaugh, 1979; Damon *et al.*, 1981; Clark *et al.*, 1982; Hausback, 1982, 1984). During the Miocene, crustal extension occurred behind the volcanic arc in the Sierra Madre Occidental forming NW-SE - trending horst and graben structures. Thick sequences of basalts, which appear widespread in the Sierra Madre Occidental, are associated with this episode of crustal extension (Cochemé and Demant, 1982; Demant and Cochemé, 1983).

Secondly, Gastil *et al.* (1978, 1979) noted that Late Miocene basalts near Tepic are similar in age to other basaltic lavas in Baja California and coastal Sonora. Recently, the tholeiitic nature of some of these basalts has been established in Baja west of Santa Rosalía (Sawlan, 1981; Sawlan and Smith, 1984). Independent studies of faulting in the Baja peninsula have demonstrated that the first important extensional episode in this region occurred in the Late Miocene when NE-SW extension produced an incipient rift or 'proto-Gulf' of California (Karig and Jensky, 1972) and tilting of fault blocks at its margins (Colletta, 1981; Colletta *et al.*, 1981; Colletta and Angelier, 1983). Late Miocene basaltic activity may be associated with this tectonic episode. At the end of the Miocene, this continental rift was invaded by the sea. Further south, Mio-Pliocene andesitic and ignimbritic volcanism at the western extremity of the TMVB was apparently related to continued subduction of the Cocos plate beneath the Mexican coast.

Major central volcanoes in the western part of the TMVB are commonly built on Mio-Pliocene ignimbrites, lavas, and tuffaceous sedimentary rocks. They are relatively small in volume (<70 km^3) compared to major volcanoes further east but their eruptive histories appear just as complex. For example, the evolution of Volcán Ceboruco (2 200 m) located 50 km southeast of Tepic (Fig. 2) can be divided into five principal stages: 1) early andesites characterized by phenocrysts of orthopyroxene and clinopyroxene rapidly built a large central volcano. A period of quiescence followed and allowed deep gulleys to be eroded in the flanks of the cone. 2) Activity resumed with ashflow eruptions (Marquesado ash) leading to the formation of a summit caldera about 3 km in diameter. Dacitic lavas flooded the southern flank and a viscous dacite dome grew inside the caldera. At about the same time, andesitic lavas were erupted low on the flanks at the ends of a NW-SE fissure system passing through the summit of Ceboruco and parallel to the dominant fault trends in the Tepic-Chapala graben. 3) The central dome was then destroyed by a second caldera collapse linked to an eccentric eruption of pumice (Jala pumice) at the southeastern end of the fissure system. This vent was eventually plugged by viscous rhyolite - rhyodacite domes while dacitic domes and flows were extruded on the northwestern flanks of the volcano. 4) Activity resumed in the summit region with the growth of a small andesitic dome within the inner caldera followed by extrusion of andesitic and dacitic lavas on the northern and western flanks. 5) Finally, the eruption of 1870 produced an andesitic flow that issued from a fissure on the southwestern flank.

The account given above differs from that of Nelson (1980) who linked the eruption of Marquesado ash and Jala pumice to the formation of the first caldera. Charcoal collected from these ash and pumice units yields ages of 1.5 and 1.0 ka (thousand years) respectively using ^{14}C methods (Nelson, 1980) which in our chronology dates the first and second caldera collapse. In comparison to Ceboruco, the caldera-forming eruption of rhyodacitic pumice at Volcán San Juan just west of Tepic (Fig. 2) took place at about 14.8 ka according to a radiocarbon date reported by Luhr (1978).

Early growth of a lava cone composed predominantly of two-pyroxene andesite is also evident at Volcán San Juan, Volcán Sangangüey, and Volcán de Tequila (described below). However, andesite flows are underlain at Sangangüey by dacitic lavas and at Tequila by rhyolites, and both volcanoes lack late-stage caldera-forming eruptions (Demant, 1981). Nelson and Carmichael (1984) indicated that the basal dacites of Sangangüey overlie peralkaline ashflow tuffs dated at 0.2 ± 0.1 Ma (S.A. Nelson, unpublished data) that were erupted from Volcán Las Navajas (Fig. 2). These data, therefore, point to the extreme youth of voluminous andesitic centers at the western end of the TMVB.

The northern part of the Tepic-Chapala graben has also been the site of Late Pleistocene to Holocene alkalic volcanism controlled by regional NW-SE oriented fissures traced locally for over 20 km and stretching through Sangangüey towards Santa María del Oro. The youngest cones and flows are composed of alkalic basalt and are locally concentrated on the flanks of Sangangüey. Older lavas occurring further southeast are typically more differentiated hawaiites, mugearites, and benmoreites (Demant, 1981; Nelson and Carmichael, 1984). Despite the large number (>40) of alkaline monogenetic cones and flows in this region their combined volume (<5 km^3) is far less than calc-alkaline lavas of Sangangüey (35 km^3) that were erupted within a similar time frame (Demant, 1981).

1b) *The Tequila Region*

This area was first studied in detail by Demant (1979, 1981). A generalized geologic map and cross-section of the Tequila area is shown in Figure 4. Volcanic rocks of the TMVB are well-exposed along the southern rim of a deep canyon cut by the Río Grande de Santiago. Older lavas and ignimbrites that crop out beneath Pliocene lacustrine deposits underlie the TMVB in this area and resemble Late Miocene to Pliocene basalts and ignimbrites found north of Guadalajara (Watkins *et al.*, 1971). Pliocene sediments in the upper part of the sequence dip gently towards the southwest (Demant *et al.*, 1976; Demant, 1979). Numerous NW-trending high-angle faults cut the Mio-Pliocene rocks and tilting of Pliocene lake beds indicate the extensional nature of this tectonic event.

The earliest Quaternary rocks that we have dated in the Tequila region are subhorizontal basaltic flows that form the Mesa Santa Rosa (Demant *et al.*, 1976, Demant, 1979). These basaltic lavas (≃100 m thick) extend from Tequila southeastwards to Arenal (Fig. 4) and were probably erupted from a fissure-type vent now covered by younger flows. The Mesa Santa Rosa basalt has a subophitic texture and contains phenocrysts of olivine(Fo_{64-57}) and labradorite(An_{63-57}) set in a groundmass of andesine(An_{48-50}), olivine(Fo_{55-49}), clinopyroxene($Wo_{43}\,En_{41}\,Fs_{16}$), magnetite, and ilmenite (A. Demant, unpublished data). The chemical composition of these lavas appears quite homogeneous and is characterized by high iron, alkalies and titania, moderate alumina, and relatively low Mg/Fe (Demant, 1981). Using the classification scheme of Irvine and Baragar (1971) these rocks are defined as hawaiites.

This basalt mesa is overlain by a glassy dacite flow well-exposed between Tequila and San Martín de Las Cañas (Fig. 4). Pumice deposits at the base of this flow re-

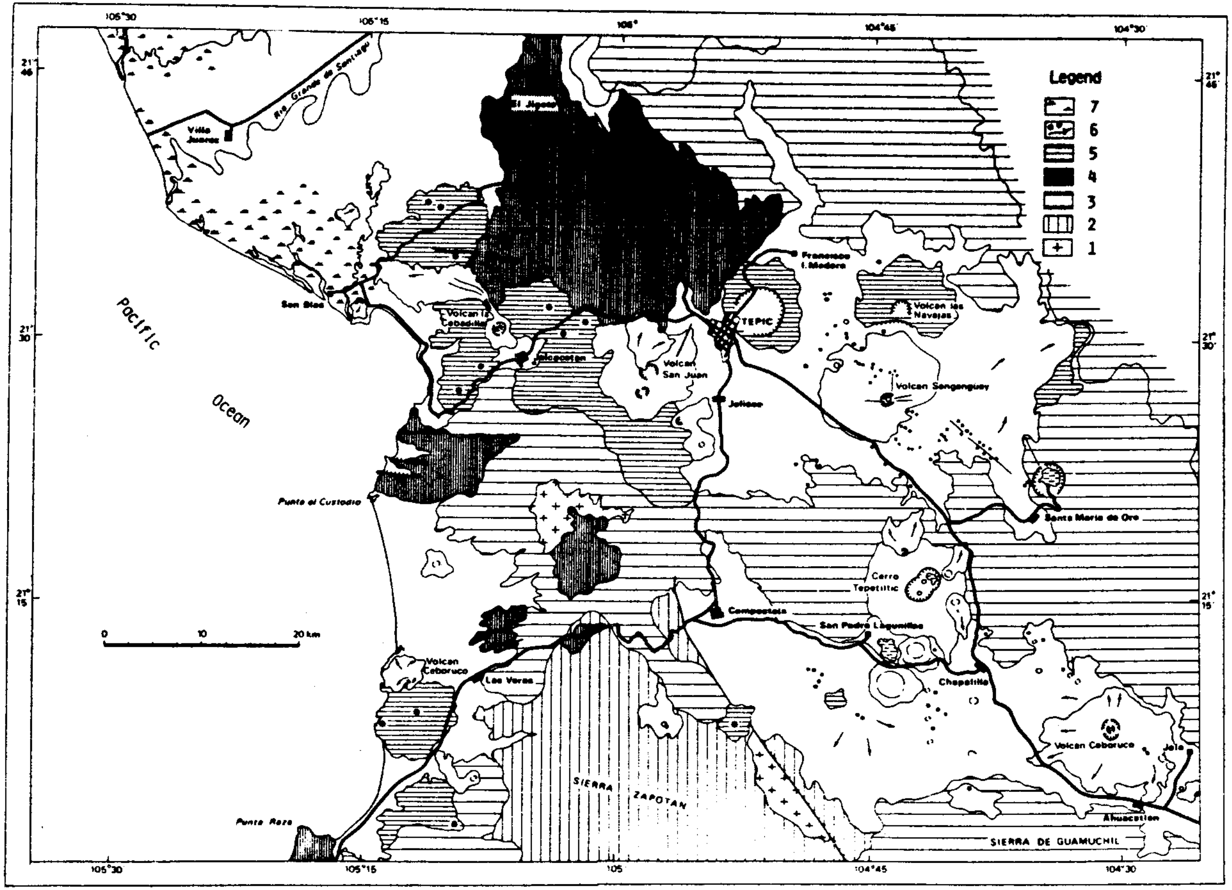

Fig. 4. Geologic map and diagrammatic cross-section of the Tequila area in the western part of the TMVB. Key to symbols: 1 = undifferentiated pre-TMVB volcanic rocks; 2 = Mesa Santa Rosa basalt; 3 = dacitic flow of San Martín de las Cañas; 4 = rhyolitic domes; 5 = andesitic flows of Volcán de Tequila; 6 = parasitic centres and flows on the east and west flanks of Volcán de Tequila; 7 = small volume pyroclastic cones and flows; 8 = Tala Tuff unit of La Primavera caldera; 9 = sample locations for K-Ar dates reported in Table 2.

present an early explosive phase of the same eruption. Both the lava and associated pumice are virtually aphyric with only a few phenocrysts of oligoclase, anorthoclase, orthopyroxene, magnetite, and ilmenite. San Martín dacite is in turn partly covered by the rhyolitic dome of Cerro Saavedra (Fig. 4). To the south and southwest of Cerro Saavedra are found numerous other rhyolitic domes and flows most of which are obsidian or sparsely-phyric rhyolite with phenocrysts of sanidine, plagioclase, orthopyroxene, magnetite and ilmenite. All these rhyolites have relatively high alkali contents and three are comenditic (Demant, 1981).

This locally bimodal basalt-rhyolite sequence is overlain by andesites of Volcán de Tequila which displays a well-preserved central plug standing inside an eroded summit crater. The cone of Tequila was constructed by successive flows of porphyritic andesite containing phenocrysts of plagioclase, augite, hypersthene, minor amphibole and Fe-Ti oxide microphenocrysts. The groundmass is generally glassy but samples from the plug contain intergranular plagioclase(An_{45-50}), biotite, and ilmenite. All these lavas have a typical calc-alkaline composition (Demant, 1981). Viscous andesitic and dacite flows that issued from vents aligned along a NW-SE fracture zone cover the eastern and western flanks of the cone and are probably related to the same magma chamber that previously erupted Tequila andesites (Fig. 4). More recent scoria and block cones scattered throughout the Tequila region range in composition from basalt to dacite. The more siliceous lavas, however, have mineralogical and chemical traits that distinguish them from the lavas of Tequila volcano (Demant, 1981).

K-Ar dates reported in Table 2 are for the Mesa Santa Rosa basalt, the dacitic flow of San Martín, and an andesite flow from the upper part of Tequila volcano. Note that there are no discrepancies between the relative ages of these rocks as given by field relationships and their K-Ar ages. The Mesa Santa Rosa basalt has an age of 0.93 ± 0.05 Ma, the dacitic flow of San Martín gave an age of 0.63 ± 0.03 Ma, and the Tequila andesite is 0.22 ± 0.03 Ma. Two additional K-Ar dates concordant with ours have recently been reported by Harris and Carmichael (1984), one for the plug of Volcán de Tequila (0.21 Ma, Table 1) and the other for the obsidian dome of Cerro Saavedra (0.55 Ma, Fig. 4). Since andesite flows of Volcán de Tequila overlie both San Martín dacite and rhyolitic flows and domes that appear similar in age to Cerro Saavedra, the cone of Tequila was most likely built between approximately 0.6 and 0.2 Ma. This estimate overlaps with the age of Sangangüey volcano (0.2 ± 0.1 Ma) as inferred by Nelson and Carmichael (1984).

Southeast of Volcán de Tequila dacitic flows of Cerro Las Garzas are covered by an ashflow tuff deposit (the Tala Tuff) related to caldera-forming eruptions at Sierra La Primavera. Since emplacement of the Tala Tuff occurred at approximately 0.1 Ma (Mahood and Drake, 1982) volcanic activity in this region appears to have been essentially continuous since at least Mid-Pleistocene.

2) *The Guadalajara Region*

The Guadalajara region, located near the intersection of the Tepic-Chapala and Colima grabens, is a zone of transition between the western end of the TMVB and the Michoacán region (Fig. 5). The principal Quaternary volcanic center, a young caldera-dome complex known as Sierra La Primavera, has received a great deal of attention in recent literature (Mahood, 1977, 1980, 1981; Mahood and Drake, 1982; Demant and Vincent, 1978; Clough *et al.*, 1981, 1982; Wright, 1981; Walker *et al.*, 1981). Ash- and pumice-flows of the Tala Tuff were emplaced concomitant with caldera collapse at about 0.1 Ma and pre- and post-caldera domes, which mark the site of caldera ring fractures, were emplaced between 0.15 and 0.03 Ma (Mahood and Drake, 1982; Table 1). All the lavas of Sierra La Primavera are mildly peralkaline rhyolites (comendites) compositionally similar to those in the Tequila region.

North of Guadalajara, the Río Grande de Santiago has carved a deep canyon in thick (700 - 800 m) volcanic formations described by Watkins *et al.* (1971). The base of the succession is formed by Late Miocene (9 Ma) basaltic flows and ashflow tuffs (Table 1). The upper part of the succession is composed of andesitic to basaltic flows and ignimbrites of Mio-Pliocene age (5.4 - 3.5 Ma). The youngest unit is an ignimbrite exposed in the northern suburbs of Guadalajara at La Experiencia (Mahood, 1977). Vitrophyric pumice-rich ignimbrites (4.7 Ma) in the upper part of the Río Grande de Santiago sequence are mineralogically complex with phenocrysts of plagioclase, orthopyroxene, clinopyroxene, hornblende, biotite, sparse olivine, and numerous xenoliths of rhyolite and basalt. Ignimbrites of similar character are observed east of Guadalajara near Tototlán (Fig. 5) and near Acatlán to the south, as well as further east near the Huichapan and Amealco calderas on the northern fringe of the TMVB (Demant, 1981; Fig. 2). The stratigraphic succession recognized by Watkins *et al.* (1971) in the Guadalajara region, *viz.* Late Miocene basalts underlying Pliocene calc-alkaline rocks (basaltic to dacitic flows and silicic ignimbrites), extends beneath the Mesa Santa Rosa basalt north of Tequila and appears correlative to sequences described by Gastil *et al.* (1979) in the Tepic region. East of Guadalajara, in the area between Atotonilco El Alto-Ayo El Chico and Tepatitlán-

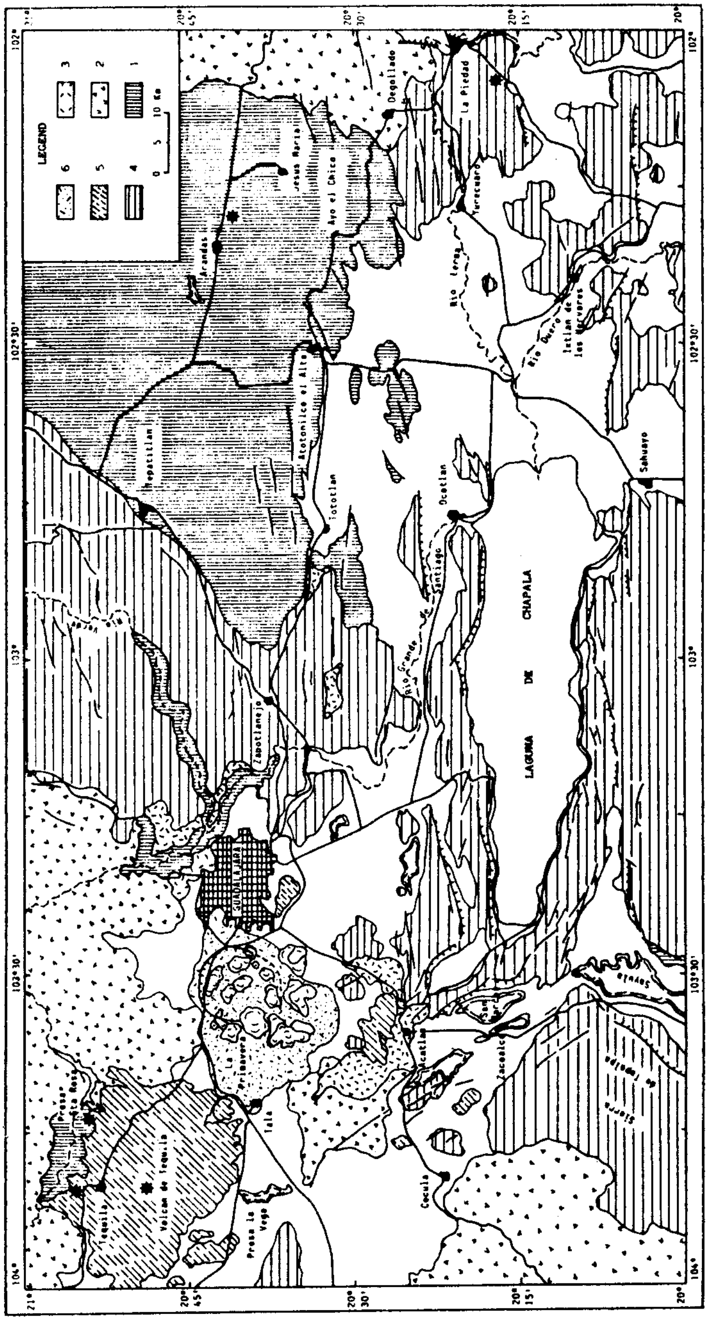

Fig. 5. Generalized geologic map of the Guadalajara region. Key to symbols: 1 = Late Miocene volcanic rocks; 2 = Pliocene ignimbrites; 3 = Plio-Quaternary ignimbrites with complex mineralogy (augite+ hyperstene+ hornblende+ biotite ± olivine) and abundant xenoliths; 4 = Plio-Quaternary volcanic rocks (mainly andesitic); 5 = Quaternary volcanic rocks of the TMVB; 6 = Late Pleistocene comenditic domes and tuffs of Sierra La Primavera. Asterisks indicate sample locations for K-Ar dates reported in Table 2.

Arandas (Fig. 5), gently dipping basaltic lavas form an extensive plateau cut by E-W striking normal faults that skirt the northern margin of the Lake Chapala depression. On palaeomagnetic grounds, Urrutia and Pal (1977) proposed that these basalts were Oligocene in age whereas Robin and Nicolas (1978) tentatively correlated them with Plio-Quaternary basalts in eastern Mexico. A new K-Ar date on a basalt near Arandas yielded an age of 10.2 ± 0.3 Ma* (sample 1131, Table 2). These basalts are therefore similar in age to those dated by Gastil *et al.* (1978, 1979) west of Tepic and volcanic rocks in the canyon of the Río Grande de Santiago. Thus, basaltic lavas of Late Miocene age appear to be widespread in this part of Mexico.

3) *The Colima Graben*

The distinct N-S trend of the Colima graben extends from the western tip of Lake Chapala almost to the Pacific coast, a distance of some 200 km (Fig. 2). A recent study of the Colima graben by Allan (in press) has revealed some interesting differences in structural style between the Colima and Tepic-Chapala grabens. In that part of the Tepic-Chapala graben that lies immediately northwest of the mouth of the Colima graben, named the Zacoalco graben by Allan (*ibid.*; Fig. 5), fault-blocks have been rotated towards the northeast and are bounded by SW-dipping normal faults that appear listric in nature. This style of faulting is prominent in regions of extensional tectonism like the Basin and Range Province. Fault-blocks in the Colima graben, on the other hand, are bounded by steeply dipping normal faults and show no evidence of rotation, possibly indicating a deeper root zone than their counterparts in the Zacoalco graben (Allan, in press). Although faulting in both grabens has been shown to extend into the Late Pleistocene, the age for the inception of graben development is unknown. Díaz and Mooser (1972) suggested that extensive normal faulting in the vicinity of Lake Chapala and the northern Colima graben began in the Pliocene.

The major volcanic centers in this part of the TMVB are Nevado de Colima and Volcán de Colima which form two overlapping cones that culminate at altitudes of approximately 4 320 m and 4 300 m respectively. Together, these volcanoes have a total volume in excess of 450 km^3 (Luhr and Carmichael, 1981) which is nearly an

---

* Verma *et al.* (1985) have also dated basalts of the Atotonilco El Alto-Arandas area. Of four samples analyzed, three gave Late Miocene ages (10 - 12 Ma) and one an Oligocene age (32 Ma). The latter date appears anomalous since it comes from the same volcanic center as one of their samples dated at 11 Ma. These results are not included in Table 1.

order of magnitude greater than major volcanoes to the west but comparable to volumes of the largest cones in the eastern part of the TMVB (Nixon, 1982). About 17 km north of Nevado de Colima occurs an older more eroded volcanic complex, Cerro El Cántaro (2 925 m), composed of coarsely porphyritic andesite lavas. Rocks of similar morphology are found further north along the western margin of the Colima graben.

As a result of recent studies (Demant, 1979, 1981; Luhr and Carmichael, 1980, 1982; Robin *et al.*, 1984) the evolution of the Colima volcanoes is now more completely understood and four main phases of activity have been recognized: 1) Nevado de Colima is a large composite volcano whose flanks are mantled by thick conglomeratic deposits known as the Atenquique Formation (Mooser, 1961). These clastic units contain mainly andesitic cobbles and may in part represent flow or collapse breccias. They seem to have been laid down more or less contemporaneously with development of the initial cone (Nevado I of Robin *et al.*, 1984) which was partly destroyed by summit collapse accompanying the deposition of pyroclastic flows. Later growth of a new andesitic cone (Nevado II) within the caldera of Nevado I also culminated in collapse of its summit as a result of violent pyroclastic eruptions (Robin *et al.*, 1984). 2) Nested within the summit caldera of Nevado de Colima and forming the peak region of the volcano is the Picacho, a lava cone built by rapid extrusion of viscous dacitic flows (Demant, 1979, 1981). The form of this volcano has been severely modified by glacial ice and its present volume is about 10 km^3. 3) Volcán de Colima has been built on the southern flank of Nevado I and is equivalent in age to Nevado II. This volcano was partly destroyed by a cataclysmic caldera-forming eruption apparently similar to the May 1980 eruption of Mt. St. Helens (Luhr and Carmichael, 1982). The northern rim of its horseshoe-shaped caldera is well preserved but the southern margin is buried by the post-caldera cone. The exact age of caldera formation is uncertain. Luhr and Carmichael (1982) linked a scoria-fall horizon bracketed at 4.3 ka by ^{14}C methods with the caldera-forming event. However, Robin *et al.* (1984) related debris flows covering the southern slopes of Volcán de Colima with this event and reported a ^{14}C date of 9.6 ka. Plinian airfall tephra are associated with some of the most recent eruptions of this volcano. 4) Volcán de Fuego has been the most active volcano in Mexico within historical time. A summary of the history and cyclicity of eruptions is given by Luhr and Carmichael (1980). Located within the caldera of Volcán de Colima, Volcán de Fuego has a structural disposition analogous to the Picacho (Demant, 1981). Distinct cycles of eruptive activity separated by periods of quiescence may be identified within the historical record. Each cycle is characterized by emission of lava flows from the summit crater and short but violent explosive eruptions that produce St. Vincent-type nuées ardentes such as those observed by Waitz (1920, 1936). These explosive phases appear to be triggered by an influx of olivine-phyric basaltic liquid into the magma chamber (Luhr and Carmichael, 1980, 1982; Demant, 1981). The nuées ardentes stage of activity coincides with the beginning of an eruptive cycle (Demant, 1981) rather than the end of the cycle as suggested by Luhr and Carmichael (1980). This interpretation is based on the numerous inclusions of two distinct magma compositions - basaltic scoriae and andesitic pumice - that coexist in the pyroclastic deposits. Succeeding lava flows, on the other hand, lack such inclusions but do contain sparse olivine xenocrysts indicating that basaltic and andesitic magmas gradually became more homogenized as eruptions continued.

K-Ar dates for Nevado de Colima have recently been published by Robin *et al.* (1984). Andesitic flows located near the base of the cone (Nevado I) range in age from 0.53 to 0.37 Ma whereas the uppermost flows (Nevado II) have ages of 0.29 to 0.14 Ma (Table 1). The youngest date (0.08 Ma) was obtained on a block in a pyroclastic flow deposit sampled near Atenquique. This deposit is believed to be related either to the final phases of eruptive activity of Nevado II or to the Picacho. In any case, it is clear that the Picacho was built contemporaneously with Volcán de Colima. Volcán de Fuego, on the other hand, has been built within the Holocene.

In addition to the large volumes of calc-alkaline andesite that form the Colima-Cántaro volcanic complex, the Colima Graben is occupied by monogenetic cones and flows of high-alumina basalt, dacite, and unusual K-rich basanites and lamprophyric rocks. The latter group of rocks form Late Pleistocene to Holocene scoria cones and flows that are almost exclusively confined to the lower northeastern flank of Nevado de Colima (Luhr and Carmichael, 1981). Injections of lamprophyric liquid into calc-alkaline magma reservoirs feeding the Colima-Fuego system are believed to be responsible for alkaline scoriae and ash layers of Holocene age on the flanks of Volcán de Colima (Luhr and Carmichael, 1982). More recently, lamprophyric rocks have also been discovered in the walls of the Colima graben together with andesitic lavas and a phlogopite-kalsilite ankaratrite (Allan and Carmichael, 1984).

Allan (in press) has recently reported more than 30 K-Ar dates for rocks in the Zacoalco and Colima grabens (Table 1). These data are shown in a frequency plot in Figure 6 and compared with rocks of similar age in the Tepic-Guadalajara region.

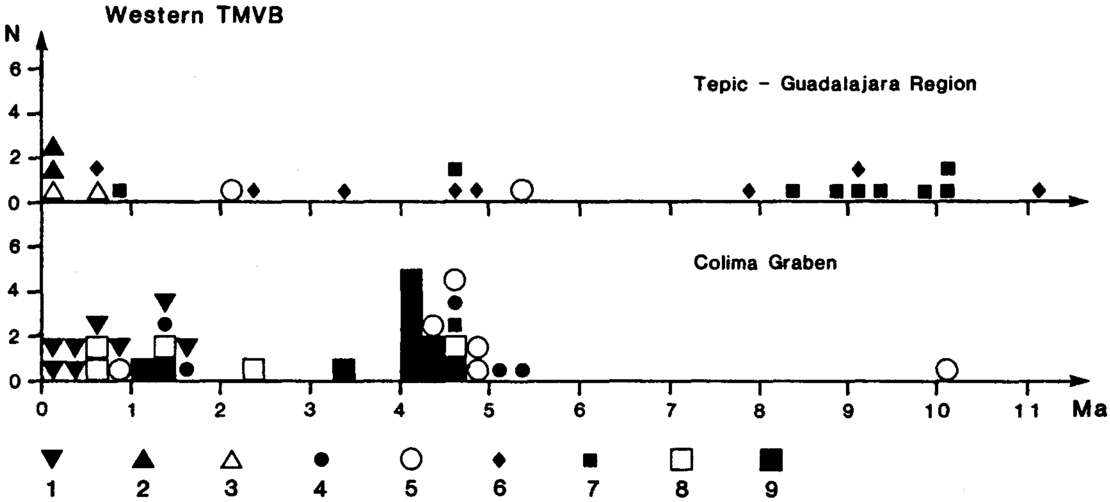

Fig. 6. Histogram of K-Ar dates of Mid-Miocene to Quaternary volcanic rocks in the western part of the TMVB. Key to symbols: 1 = Cántaro-Colima volcanic complex; 2 = andesites of Tequila volcano; 3 = dacites; 4 = hornblende ± biotite andesite/dacite; 5 = andesite; 6 = rhyolite/ignimbrite; 7 = basalt; 8 = high-K andesite; 9 = K-rich lamprophyre.

Note the diversity of rock types erupted in the Colima graben since Early Pliocene and the bimodal nature of Mio-Pliocene volcanism further north in the Tepic-Chapala graben. The earliest occurrence of potassic volcanism dates back to 4.7 Ma when ankaratrite magma vented 40 km north of the future site of the Colima volcanoes. Shortly thereafter (4.4 - 4.2 Ma) isolated lamprophyric centers erupted throughout a 50 km segment of the Colima graben north of 19°40′N and activity continued intermittently into the Quaternary. High-K andesites appear to share a similar eruptive history and exhibit mineralogical and compositional gradations towards the lamprophyric suite (Allan and Carmichael, 1984). Early lamprophyres were erupted contemporaneously with calc-alkaline andesites and dacites analogous to their Late Quaternary counterparts. Most recent alkaline activity is focused between latitudes 19°37′ and 19°46′N just behind the trenchward limit of calc-alkaline volcanism, as defined by Volcán de Colima (19°30′N), and occurs slightly south of the southernmost outcrops of Early Pliocene lamprophyres. Alkaline volcanism within the Colima graben south of the 'volcanic front' is presently unknown.

The most recent episode of calc-alkaline volcanism in the Colima and Zacoalco grabens began approximately 1.7 - 1.4 Ma with the extrusion of hornblende ± biotite andesitic to dacitic flows and domes (B13 and M169, Table 1). Lavas of the deeply dissected Cántaro volcanic complex north of Nevado de Colima yield ages of 1.4 - 0.95 Ma in comparison to the more youthful Colima volcanoes dated at 0.53 - 0.08 Ma (Robin *et al.,* 1984). Relative to outcrops of Miocene and Early Pliocene andesites, the largest volume of Quaternary andesitic lava in the Colima graben has erupted further south nearer the Middle America Trench.

THE CENTRAL PART OF THE TMVB

The central part of the TMVB is described below in terms of three geographic regions. From west to east these regions are: 1) the Michoacán volcanic zone; 2) the Toluca region; and 3) the Valley of Mexico and Sierra Nevada.

1) *The Michoacán Volcanic Zone*

East of Lake Chapala, the character of Quaternary volcanism changes conspicuously such that large volcanoes are absent and small volume cones and flows dominate the landscape. This type of volcanic activity has become known as areal volcanism in that some 3 000 cones occupy an area of approximately 40 000 km^2 (0.08 per km^2). The Michoacán region first gained prominence in the literature with the eruption of Paricutín volcano in the years 1943-1952 (Segerstrom, 1950; Williams, 1950; Wilcox, 1954). However, volcanic activity appears to have been most intense during the Late Pleistocene and early Holocene.

The geographic boundaries of the Michoacán volcanic zone are delineated by the 18°45′ and 20°15′ parallels and the 100°25′ and 102°45′ meridians. In the north, the volcanic zone extends into southern Guanajuato where it is limited in the north by a topographic depression known as El Bajío running NE-SW along the southern margin of a high plateau underlain by Tertiary ignimbrites that extend from northern Jalisco to San Luis Potosí. To the west the Sierra de Jiquilpan composed of Mesozoic basement covered by Mio-Pliocene volcanic rocks overlooks the eastern margin of the Colima graben. The southern margin of the volcanic zone borders the Río Tepalcatepec which skirts the high coastal sierras (Fig. 2). In the latter region, basaltic plateau lavas similar in appearance to those of the Atotonilco El Alto - Arandas area cover Mesozoic rocks and Late Tertiary volcanic sequences (Demant, 1981). Further east these rock formations are folded to form a broad NNW-SSE - trending structure, the Tzitzio-Huetamo anticline (Mauvois *et al.,* 1976). Rocks on the eastern limb of this anticline in the Mil Cumbres area have Miocene ages (14.1 Ma, Table 1). The eastern margin of the Michoacán volcanic zone is marked by a series of NNW-SSE - trending lineaments conspicuous on ERTS-LANDSAT imagery and named the Querétaro-Taxco fault system (Demant *et al.*, 1976; Fig. 2). The location of these faults coincides with the main overthrusts of the Cordilleran System (Córdoba *et al.*, 1980; Fig. 1). The orientation of faults in western Michoacán is generally northwest-southeast or east-west, but northeast-southwest trends are common in the eastern part of the state. Many of these faults cut only pre-Quaternary rocks. Monogenetic volcanoes do not appear to be controlled by any single fault system as appears common in the Tepic-Chapala region, and instead reflect the greater complexity of basement fracture patterns.

The volcanic cones of Michoacán seldom achieve volumes in excess of 10 km^3. Cerros Patamban and Tancítaro are among the largest volcanoes with volumes approaching 30 km^3 and 60 km^3 respectively. South of Cerro Tancítaro (3 900 m) elevation decreases rapidly, descending to about 400 m in the vicinity of Nueva Italia some 40 km to the southeast. Extensive conglomeratic fans, partly obscured by Holocene scoria cones and flows, can be traced from the base of Tancítaro to the Tepalcatepec depression (Demant, 1981).

A progressive change in volcanic activity in time and space has been inferred from field mapping in the Michoacán region (Demant *et al.*, 1976; Demant, 1981). In northern Michoacán, many cones and flows appear morphologically old and are commonly cut by normal faults. Examples of such structures are Cerro Grande near La Piedad, Cerro de La Gavia, and Cerro Culiacán, all of which are basaltic to andesitic in composition (Fig. 2). The degree of erosion of these volcanoes is similar to that of small cones dispersed on the Atotonilco El Alto - Arandas plateau and east of Guadalajara around the northern margin of the Tepic-Chapala graben (these cones are not shown on the geologic maps). Small dacitic domes with phenocrysts of hornblende and biotite are also common in this region in addition to ignimbrites that mineralogically and compositionally resemble those north of Guadalajara (Demant, 1981). Source calderas for the pyroclastic rocks have been identified northwest and southeast of Querétaro; the Amealco caldera is one of the best preserved (Sánchez-Rubio, 1978; Fig. 2). The products of more recent volcanism in southern Michoacán appear to be dominantly andesitic with subordinate basalts and dacites. Rhyolites are comparatively scarce except for the dome-and-flow complex of Sierra Los Azufres (Fig. 2).

Rock samples selected for K-Ar dating in Michoacán were specifically chosen to test the relationships between age of eruption and cone degradation inferred from field mapping. Sample 881, a hornblende dacite dome named Cerro Alto located northeast of Cerro Patamban and about 20 km west of Zamora is Late Pliocene (2.6 ± 0.1 Ma, Table 2; Fig. 2). Sample 706, a basaltic flow erupted from the cone of Cerro Grande (600 m) near La Piedad, is Quaternary (1.6 ± 0.1 Ma; Figs. 2 and 5). Both volcanoes were mapped as part of the Plio-Quaternary succession by Demant (1981). Sample 340 collected from the lava cone of Cerro Sanambo 10 km northeast of Pátzcuaro Lake has a Late Pleistocene age (0.87 ± 0.05 Ma). Additional K-Ar dates for rocks in northeastern Michoacán have been published by Demant *et al.* (1975). An obsidian from the Los Azufres complex near Ucareo gave an age of 1.6 Ma and two rhyodacite domes in the Tuxpan region 40 km southeast of Los Azufres are Late Pleistocene (0.36 - 0.05 Ma, Table 1). The latter rocks occur in close proximity to the volcanic front in this part of Michoacán which is locally displaced northwards away from the trench.

The K-Ar dates reported above support field evidence for a general southward migration of calc-alkaline volcanism since at least the Late Pliocene. The locus of recent volcanism is superposed on Miocene volcanic rocks which crop out along the northern and southern margins of the TMVB. Pliocene andesitic and ignimbritic volcanism appears widespread in northern Michoacán and Guanajuato (Demant, 1981). Late Pleistocene - Holocene andesitic volcanoes are concentrated in southern Michoacán but Recent activity is not confined to the volcanic front. For example, alkaline maars of probable Holocene age in the Valle de Santiago erupted in a 'backarc' environment (Fig. 2).

2) *The Toluca Region*

South of the city of Toluca occurs the major volcano of Nevado de Toluca and in addition monogenetic cones and flows of Late Pleistocene to Holocene age. According to Cantagrel *et al.* (1981), two episodes of volcanism can be distinguished at Nevado de Toluca. An early phase of growth represented by lava flows and 'conglomeratic' deposits of two-pyroxene andesite produced a volcanic substructure that accounts for most of the cone's present volume. K-Ar dates on andesitic lavas *in situ* and transported cobbles in the clastic beds range from 1.6 to 1.2 Ma (Table 1). Prolonged erosion of this early cone was followed by renewed volcanic activity assumed to have commenced at approximately 0.1 Ma. Pyroclastic flow deposits were emplaced on the flanks of the eroded substructure and accompanied the formation of a summit caldera. Extrusion of hornblende ± biotite dacite flows and domes postdated caldera collapse. Opening of the present summit crater began with a series of Plinian eruptions that deposited the Lower and Upper Toluca Pumice units at approximately 24.5 and 11.6 ka respectively according to radiocarbon dating (Bloomfield and Valastro, 1974, 1977). This phase of activity came to an end with the extrusion of a dacite dome, El Ombligo, within the summit crater. The only reported K-Ar dates on these younger dacites gave anomalously old ages (2.7 - 24.7 Ma cited by Bloomfield and Valastro, 1977).

Late Pleistocene to Recent pyroclastic cones and flows of basaltic to dacitic composition occur east of Nevado de Toluca at Tenango (Bloomfield, 1973) and Tenancingo (Cantagrel *et al.*, 1981), and in the Río Lerma basin southeast of the city of Toluca (Bloomfield, 1975; Fig. 2). Short E-W alignments of scoria cones are common in the latter region. On the basis of cone morphology and ^{14}C-dating, Bloomfield (1975) concluded that these volcanoes formed during the last 40 ka and correlated these rocks with the Chichinâutzin Group of the Valley of Mexico (Fries, 1960).

3) *Valley of Mexico and the Sierra Nevada*

Quaternary volcanism is widespread within the Valley of Mexico and the Sierra Nevada (Fig. 2). The Valley of Mexico is a basin extending over 100 km from north to south and varying in width from 30 to 60 km. It is underlain by lacustrine sediments, alluvial fill, Tertiary volcanic rocks, and Cretaceous limestones (Schlaepfer, 1968; Mooser *et al.*, 1974). The limits of this basin are defined by the following topographic barriers: to the north lie the Sierras Tezontlalpan and Pachuca near the eastern margin of the Sierra Madre Occidental province (Demant and Robin, 1975); to the south the basin is choked by young volcanoes of the Sierra Chichinâutzin; to the west lie Tertiary volcanic rocks of the Sierra de Las Cruces; and to the east the Sierra Nevada and Sierra Río Frío. The southern extremity of the Sierra Nevada is formed by Popocatepetl (5 452 m) and the central part by Iztaccíhuatl (5 286 m) whose northern flanks extend almost as far as the highway linking Mexico City and Puebla. From this location the Sierra Río Frío continues northwards towards Pachuca eventually dying out northeast of Teotihuacân.

Popocatépetl is the only historically active volcano in the Sierra Nevada (Mooser *et al.*, 1958). Its early evolution appears similar to that of its northern neighbour Iztaccíhuatl (described below). Older lavas underlying the northern slopes of the volcano are two-pyroxene andesites and dacites with accessory olivine and rare amphibole phenocrysts. The most recent phase of activity probably began towards the end of the Pleistocene with the construction of a symmetrical summit cone crowned by an explosion crater 500 m across and 300 m deep. Dark grey crystal-vitric ash mantles the crater rim and dacitic airfall pumice blanket the flanks becoming thickest east of the crater. ^{14}C-dated pumice horizons extend back to 15 ka (Heine and Heide-Weise, 1973; Lambert and Valastro, 1976). However, Holocene activity was not confined to the central vent and andesitic lavas erupted from a NE-SW fissure at the eastern foot of Popocatépetl, forming flows up to 15 km in length with a total volume of about 3 km^3.

The volcanic evolution of Iztaccíhuatl and the northern Sierra Nevada is described more fully by Nixon *et al.* (in prep.). A simplified geologic map and cross-section of Iztaccíhuatl are presented in Figure 7 and a diagrammatic summary of the evolution of this volcano is shown in Figure 8 which is based on K-Ar dates given in Table 1. Steele (1971) reported K-Ar dates for Iztaccíhuatl ranging from 13 to 5 Ma which were subsequently used by Mooser *et al.* (1974) to establish a chronology for volcanism in the Sierra Nevada beginning in the Miocene. These dates have subsequently been retracted (Steele, 1985) and we present a revised chronology below.

The volcanic stratigraphy of Iztaccíhuatl may be subdivided into two main eruptive sequences distinguished by differences in age, texture, and phenocryst mineralogy. The earliest lavas and pyroclastic rocks (the Older Volcanic Series) are composed mainly of fine- to medium-grained two-pyroxene andesites and dacites. The principal volcanic edifice at this time, a broad lava cone named Llano Grande, had already reached an altitude of some 4 000 m by 0.9 Ma and activity continued intermittently until approximately 0.6 Ma (Table 1). Parasitic vents on the northern flanks of this structure extruded andesite and rhyodacite flows, and a major volcano, Ancestral Pies, developed on its southern flank (Fig. 8). Caldera collapse of the summit region of Llano Grande probably occurred prior to 0.6 Ma. A period of intense erosion preceded the eruption of a younger group of lavas (the Younger Volcanic Series) which started at about 0.6 Ma. These lavas are coarsely porphyritic hornblende-bearing andesites and dacites with minor amounts of quartz, biotite, and olivine. A number of vents aligned NNW-SSE were active at this time until a cataclysmic eruption at the southernmost vent (Pies) terminated activity there at about 0.3 Ma. Andesites and dacites (Summit Series flows) continued to erupt from vents further north and constructed the modern peak region. At approximately 0.27 Ma basaltic to andesitic scoriae and lava flows erupted at La Joya on the southern flank of Pies, and at 0.08 Ma viscous dacite lava covered the northern slopes (Cerro Teyotl, Figs. 7 and 8). Summit vents may have remained active during the last 0.1 Ma but volcanism ceased prior to Late Pleistocene (Wisconsin) glaciation. Post-glacial dacites

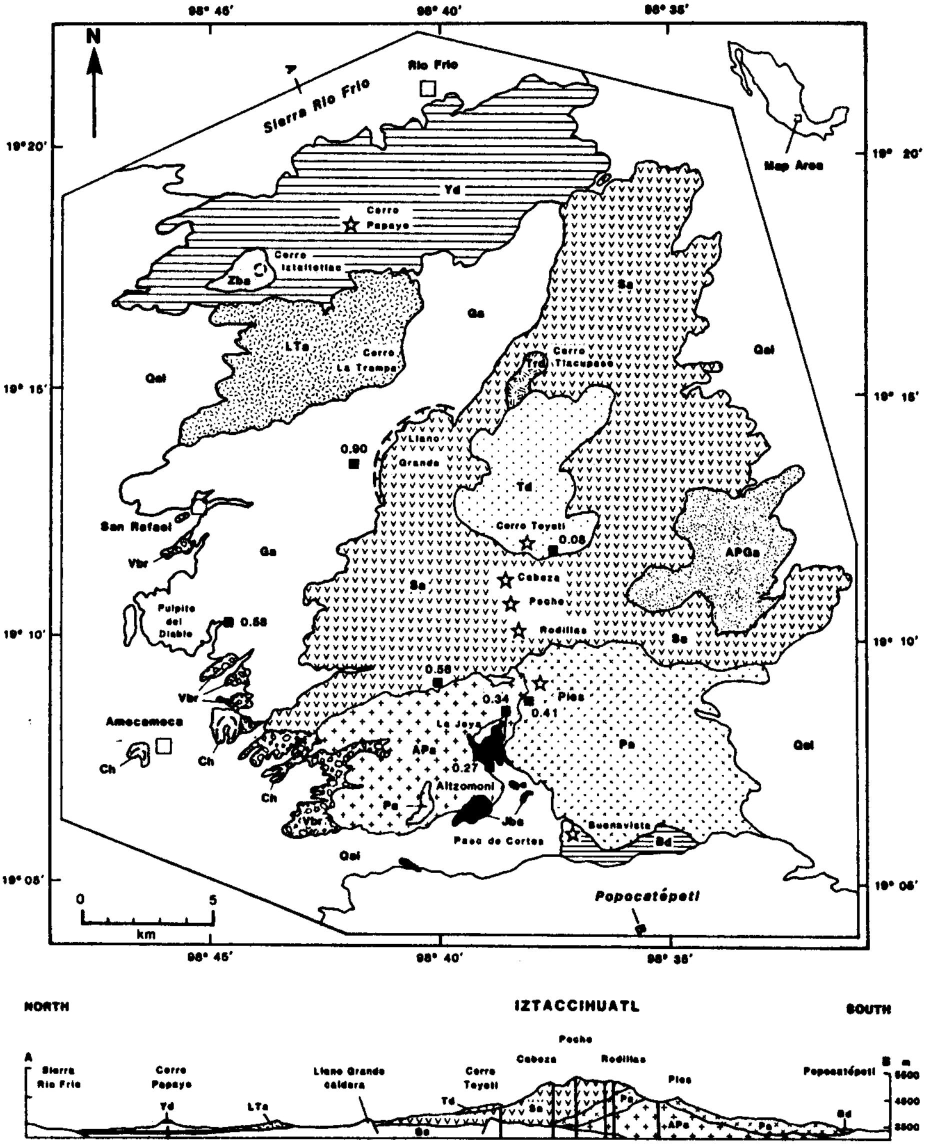

Fig. 7. Generalized geologic map and cross-section of Iztaccíhuatl volcano, Sierra Nevada, Mexico. Black squares represent K-Ar sample localities; ages are given in Ma. Key to map units: *Iztaccíhuatl - Older Volcanic Series:* Ga = Llano Grande volcano; APa = Ancestral Pies cone; APGa = undifferentiated lavas of Llano Grande and Ancestral Pies; LTa = La Trampa flows; Trd = Tlacupaso rhyodacite; *Younger Volcanic Series:* Pa = Pies lavas; Sa = Summit Series lavas; Jba = La Joya andesites and basaltic andesites; Td = Teyotl dacite; *Sierra Nevada and Valley of Mexico:* Zba = Iztaltetlac basaltic andesite; Yd = Papayo dacite; Bd = Buenavista dacite; Vbr = epiclastic volcanic breccias; Qal = alluvium, fluvioglacial deposits, loess, and airfall pumice; Ch = Chichinautzin Group cinder cones. Stars indicate source vents and dashed lines represent volcanic craters/calderas.

and pumice-flow deposits occur near Río Frío at the northern extremity of the Sierra Nevada and at Paso de Cortés, the mountain pass between Iztaccíhuatl and Popocatépetl.

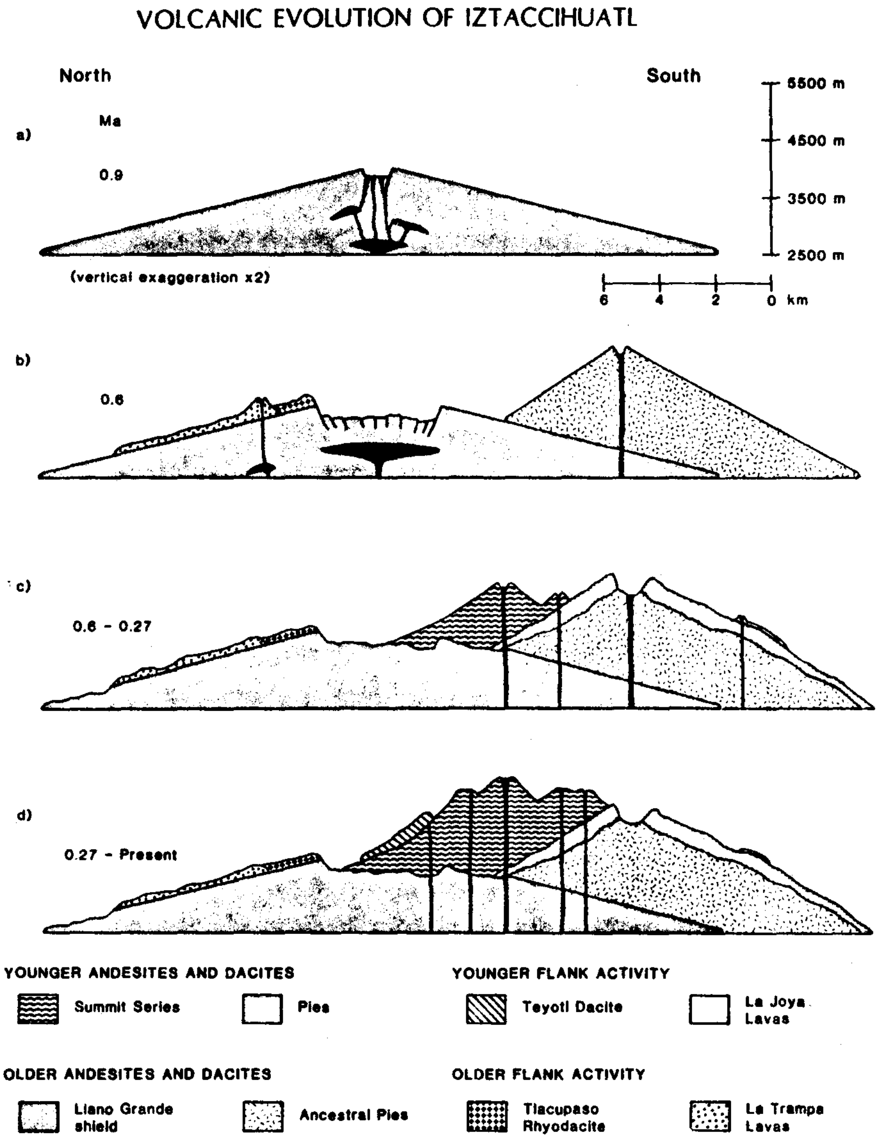

Fig. 8. Schematic chronology of the development of Iztaccíhuatl volcano, Sierra Nevada, Central Mexico.

The main stages of cone development at Iztaccíhuatl are comparable to those inferred for Nevado de Toluca by Cantagrel *et al.* (1981) although the latter volcano has not been mapped in detail. The deeply dissected substructure of each volcano is composed of relatively large volumes of two-pyroxene andesites that are overlain by more viscous dacitic lavas of the modern cone. Since Iztaccíhuatl had already developed a mature lava cone (Llano Grande) by about 0.9 Ma, we suggest that the 1.2 - 1.6 Ma andesites of Nevado de Toluca (Table 1) are correlative with this early phase of cone construction. Consequently, a nominal age of 1.7 Ma seems reasonable for the birth of major volcanoes in this part of the TMVB.

Palaeomagnetic investigations of the Sierra Nevada and Valley of Mexico have been conducted by Steele (1971, 1985), Mooser *et al.* (1974), and Herrero and Pal (1978). Younger andesites and dacites forming the Pies and Summit Series of Iztaccíhuatl (*i.e.* the Younger Volcanic Series) record only the most recent magnetic polarity interval or Brunhes chron (<0.73 Ma according to the time scale of Harland *et al.*, 1982). This inference is supported by the K-Ar dates which place an upper age limit of approximately 0.6 Ma on these lavas (Table 1 and Steele, 1985). However, sites examined by Mooser *et al.* (1974) in the Older Volcanic Series of Iztaccíhuatl, such as localities near the caldera rim of Llano Grande volcano and Púlpito del Diablo at its western margin (Fig. 7), are reversely magnetized. Therefore these rocks belong to the Matuyama reversed polarity interval (0.73 - 2.48 Ma) although late stage activity on the flanks of Llano Grande continued into early Brunhes. High on the western flank of Ancestral Pies at Altzomoni (Fig. 7) andesitic lavas with normal polarity reveal that construction of this volcano was also well advanced by early Brunhes time. Further south, rocks equivalent in age to the Older Volcanic Series extend beneath Popocatépetl and underlie the glaciated remnants of a former volcanic edifice known as Nexpayantla (Mooser *et al.*, 1958) which is exposed on the norwestern slopes of Popocatépetl. The lavas of Nexpayantla have normal polarity (Mooser *et al.*, 1974) and appear to be structurally and morphologically equivalent to late Pies flows (*ca.* 0.4 - 0.3 Ma). North of Iztaccíhuatl, deeply eroded andesitic lavas along the southern and western margins of the Sierra Río Frío exhibit both normal and reversed polarity (Mooser *et al.*, 1974). Based on their morphological resemblance to rocks of the Older Volcanic Series we suggest that these lavas straddle the Brunhes - Matuyama boundary. The correlations proposed above and the K-Ar and palaeomagnetic data on which they are based are shown schematically in Figure 9.

Palaeomagnetic evidence for Quaternary volcanism of similar age in the Valley of Mexico occurs northeast of Mexico City at Teotihuacán near the margin of the Sierra

Río Frío. In this region Mooser *et al.* (1974) recognized individual Quaternary volcanic centers with both normal and reversed directions of magnetization. Similar results were obtained on cones and flows due east of Mexico City in the Sierra de Santa Catarina. However, further south in the Sierra Chichinautzin lavas with normal polarity prevail to the apparent exclusion of reversely magnetized rocks. Mooser *et al.* (1974) concluded that recent volcanism in the Valley of Mexico began in Matuyama and continued into Brunhes. Activity then became focused south of Mexico City resulting in the formation of the Sierra Chichinautzin. We support these conclusions and note the rather similar history of recent volcanism in both the Sierra Nevada and the Valley of Mexico (Fig. 9).

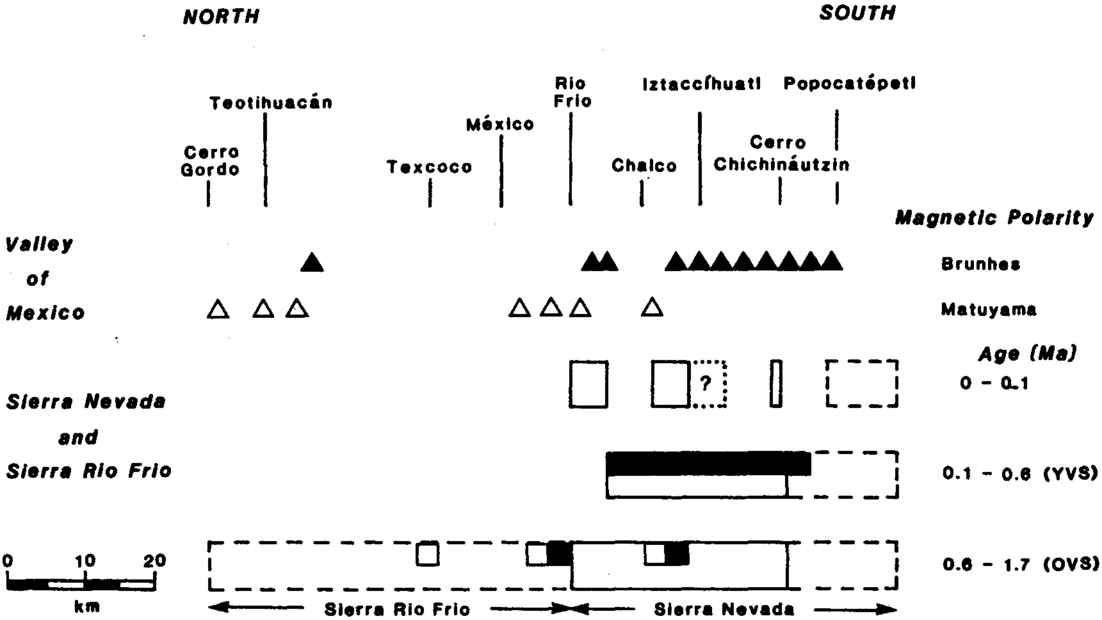

Fig. 9. Diagrammatic summary of K-Ar and palaeomagnetic data for Quaternary volcanic rocks in the Valley of Mexico and Sierras Nevada - Río Frío. Solid outlines for blocks in the lower part of the diagram indicate geologic map units for Iztaccíhuatl volcano; dashed outlines indicate the inferred extent of these units. OVS and YVS refer to the Older and Younger Volcanic Series of Iztaccíhuatl respectively.
Solid squares and triangles indicate sampling sites of rocks with normal magnetic polarity (Brunhes); open symbols are rocks with reversed polarity (Matuyama). Each triangle represents a single volcanic complex in the Valley of Mexico, except in the case of Chichinautzin Group where fewer triangles are shown. Palaeomagnetic data are taken from Mooser *et al.* (1974) and Steele (1971). K-Ar dates are given in Table 1.

Monogenetic volcanoes south of Mexico City have been studied by Martin del Pozzo (1982) who extended the relationships between ^{14}C age and cone/flow morphology established by Bloomfield (1975) for the extreme western end of the Chichináutzin Group to the region surrounding Cerro Chichinautzin, the type locality.

According to this study, all of the 140 or so cones and lava flows examined were erupted within the last 40 ka. However, dacite flows that form the Ajusco volcano on the southern outskirts of Mexico City were assigned to the Late Tertiary on her geologic map (Martín del Pozzo, 1982). The apparent youth of the Chichinautzin Group in this area is quite curious in view of the copious amounts of lava that erupted throughout Quaternary time in the nearby Sierra Nevada, and the close spatial association of small volcanoes of Brunhes and Matuyama age elsewhere in the Valley of Mexico. It may be that older lavas have been buried by the products of younger volcanism, or that this region is atypical of the Chichinautzin Group as a whole, or that the methods of comparative morphology become unreliable when applied to cones older than about 20 ka (*cf.* Luhr and Carmichael, 1981). The most likely explanation will no doubt only be clarified by additional isotopic dating. When the glaciated morphology of Ajusco volcano is compared to the relatively advanced state of erosion exhibited by Quaternary rocks of the Sierra Río Frío, it seems more appropriate to regard this volcano as Pleistocene. Of two palaeomagnetic determinations made on Ajusco dacites by Mooser *et al.* (1974) only a single normal polarity measurement was regarded as satisfactory and thus points to a Brunhes age for this volcano.

When K-Ar and palaeomagnetic data are combined, space - time patterns in recent volcanism become apparent (Fig. 9). Evidence in the Valley of Mexico suggests that monogenetic volcanism has migrated from north to south during the Quaternary whereas in the Sierras Nevada and Río Frío no such migration is evident but rather activity in the southern part of the chain is longer lived. Considering the extremely low erosion rates in the Valley of Mexico during the Pleistocene compared to the neighbouring Sierras, we feel that the most satisfactory explanation for these contrasting patterns is that the products of early Quaternary volcanism in the southern part of the Valley of Mexico have been largely buried by Brunhes volcanoes. Thus, the latest phase of voluminous andesite-dacite volcanism in this region, previously estimated to have begun at approximately 1.7 Ma, affected the entire width (>80 km) of the modern arc and one million years after its inception had built the chain of volcanoes that presently define the eastern margin of the Valley of México. By about 0.5 Ma large volcanoes in the northern part of the arc had become extinct whereas new vents opened further south initiating a second major phase of cone growth in the Sierra Nevada. Activity persisted throughout historic time at the southern end of this mountain range as Popocatépetl culminated a third major phase of cone construction not represented by volcanoes further north.

THE EASTERN PART OF THE TMVB

The eastern part of the TMVB extends from the Sierra Nevada eastwards towards the Gulf of Mexico and includes the major volcanoes of La Malinche and Pico de Orizaba (Figs. 1 and 2). The geographic limit of the TMVB in the east is located where the Altiplano descends some 2 000 m to the Gulf Coastal Plains. Further east Quaternary volcanic rocks occur at San Andrés Tuxtla near the margin of the Gulf of Mexico. However, these lavas are alkalic basalts of sodic affinity and are not considered an integral part of the TMVB (Pichler and Weyl, 1976; Thorpe, 1977). Instead, the Tuxtla volcanoes appear to represent the youngest manifestation of volcanism within an eastern alkaline province of Oligocene to Quaternary age that stretches northwards along the Gulf Coast and Altiplano margin (Demant and Robin, 1975; Robin and Nicolas, 1978; Robin, 1982). The edge of the Altiplano is marked by a series of high-angle faults trending approximately north-south to northwest-southeast. A major volcanic lineament 80 km in length including Cofre de Perote in the north to Pico de Orizaba in the south indicates the control that fractures parallel to the Altiplano border have had on TMVB volcanism in this region. Monogenetic cones and flows, many of which appear to be Late Pleistocene to Holocene in age, are much more widely dispersed than their counterparts in the Valley of Mexico. Rhyolite domes and associated pyroclastic deposits and basaltic maar volcanoes occur in the northern part of the TMVB west of Cofre de Perote. Basaltic to andesitic scoria cones and flows are common further south (Ciudad Serdán region) just west of Pico de Orizaba at the trenchward limit of Quaternary volcanism.

The cone of La Malinche (4 420 m) is built on Mesozoic limestones and Palaeozoic schists of the Acatlán Complex exposed further south (Erffa and Hilger, 1975; Ortega-Gutiérrez, 1978). Its peak region is composed of viscous hornblende dacite flows mineralogically similar to lavas forming the Younger Volcanic Series of Iztaccíhuatl and upper part of Nevado de Toluca. The flanks of the volcano are draped by thick deposits of loess and dacitic pumice ejected during recent eruptions which destroyed the uppermost part of the cone. Radiocarbon dates on palaeosols intercalated with these pumice horizons indicate that the most recent activity occurred at approximately 28 ka and 12-8 ka (Heine and Heide-Weise, 1973). Thus, the late eruptive history of La Malinche is quite similar to that of Nevado de Toluca. We suggest that the earliest volcanism at La Malinche occurred in the Pleistocene as opposed to the Pliocene age advocated by Erffa and Hilger (1975).

Pico de Orizaba (5 675 m) is the highest of the Mexican volcanoes and has a structural disposition like that of Popocatépetl in the Sierra Nevada although it has been historically less active (Mooser *et al.*, 1958). It occupies the southern extremity of a major chain of volcanoes that extends through Cofre de Perote some 60 km to the north (Fig. 2). According to Robin and Cantagrel (1982) three principal stages of cone development can be recognized at Pico de Orizaba: 1) A basal volcanic complex composed mainly of two-pyroxene andesite flows and minor basalt and dacite was formed by two eruptive centers, one beneath Pico de Orizaba and the other a parasitic cone known as Sierra Negra situated on the southwestern flank of this primitive structure. 2) Following a period of erosion, explosive eruptions demolished the summit region of the main cone producing a large caldera and thick nuées ardentes deposits on the flanks. Viscous flows and domes of hornblende dacite extruded into the caldera were later destroyed by another series of caldera-forming eruptions accompanied by more pyroclastic flows. Thus far, the evolution of Pico de Orizaba closely resembles that of Nevado de Toluca as described by Cantagrel *et al.* (1981). 3) The final phase of activity began at approximately 13 ka according to ^{14}C dates obtained by Robin and Cantagrel (1982). Powerful Plinian eruptions excavated a crater 5 km across in which stands the present summit cone (1 500 m above its base). Within the last 5 ka quiet effusive activity in the form of two-pyroxene andesite flows has become more common. By analogy with Nevado de Toluca, Robin and Cantagrel (1982) inferred that construction of the basal volcano was initiated prior to 1 Ma and assumed that the second stage began at about 0.1 Ma; no new K-Ar dates were reported.

The peak region of Cofre de Perote is a glacially eroded remnant of a large central volcano composed chiefly of two-pyroxene dacitic flows that carry minor olivine and amphibole phenocrysts. These dacites are compositionally distinguished from those of Pico de Orizaba by relatively high K_2O contents (Demant, 1981). Holocene flows of alkali olivine basalt composition are found northeast of Cofre de Perote at the Altiplano margin.

Quaternary volcanism of quite different character occurs at Los Humeros about 25 km northwest of Cofre de Perote (Fig. 2). The geology of this region has been described by Pérez-Reynoso (1978), Ferriz and Yáñez (1981), Demant (1981), and Ferriz (1985). The Los Humeros volcanic massif constitutes a broad shield rising 300 - 400 m above the surface of the Altiplano. Mesozoic limestones underlying the volcano are well-exposed to the north and occur as isolated inliers to the south. The summit of the shield is crowned by a large caldera, approximately 15 km in diameter, whose southwestern rim and entire northern margin are buried by younger lavas. Pre-caldera rhyolite and obsidian exposed by ring-faults, and aphyric·lavas of intermediate composition, form the western and southeastern caldera walls respectively.

The most abundant products of post-caldera volcanism are rhyolitic ignimbrites, dacitic to rhyolitic flows and domes, airfall pumice, and basaltic scoriae and lava flows. Caldera collapse appears to have occurred contemporaneously with the emplacement of Plinian-type pumice horizons and pyroclastic flow deposits. During the later stages of activity basaltic and rhyolitic tephra were erupted simultaneously from centers located within the caldera.

The final phases of volcanism at Los Humeros occurred late within the Quaternary when alkalic basaltic lavas were extruded just within the western part of the caldera and flooded a much smaller collapse caldera (La Calderita) situated within the southwestern margin of the larger structure (Demant, 1981). On the whole, post-caldera volcanism appears quite young morphologically. Recently reported K-Ar dates (*cf.* Ferriz, 1985) on pre-caldera mafic flows have yielded ages of 3.5 and 1.6 Ma whereas the inception of silicic pyroclastic volcanism related to caldera formation is placed at approximately 0.47 Ma. Eruptive activity ceased with the emplacement of basalt flows (La Calderita) at about 0.02 Ma (Ferriz, 1985). Rhyolitic domes just south of Los Humeros have ages of 1.2 - 0.5 Ma (H. Ferriz cited in Verma, 1984). Isolated occurrences of rhyolite domes and associated pyroclastic rings are relatively common in this part of the Altiplano and many of these complexes are unlikely to be linked with magma chambers at Los Humeros.

K-Ar dates for the eastern part of the TMVB have been reported by Cantagrel and Robin (1979; Table 1). Beyond the northern margin of the TMVB in the vicinity of Pachuca, Mio-Pliocene basalts and ignimbrites are overlain by Late Pliocene basaltic lavas (the 2.5 Ma Atotonilco El Grande flows) that appear to be restricted to the Altiplano margin. These younger lavas have geochemical attributes that render them transitional between the calc-alkaline and alkaline suites of the TMVB and Gulf Coastal Plains respectively. Cantagrel and Robin (1979) suggested that these basalts represent the earliest manifestations of the 'Neovolcanic' belt which they placed at 2.5 - 3 Ma and noted that younger calc-alkaline volcanism is focused south of this region (*i.e.* in the area shown in Fig. 2 as representing the TMVB).

Cantagrel and Robin (1979) also reported dates for the 'Pico de Orizaba volcanic complex' and presented a composite cross-section oriented N45E extending from Pico de Orizaba to the Gulf Coast onto which K-Ar ages and geologic relations were projected. In reference to Pico de Orizaba they state 'The base of the Quaternary composite volcano, mainly formed by porphyritic andesites, has an age of about 1.5 Ma (VE52)' (Cantagrel and Robin, 1979, p.107-108). We wish to point out that all of their dated samples from the 'Pico de Orizaba volcanic complex' were taken from localities 65 km or more to the north of Pico de Orizaba and it appears that the geology has been projected a similar distance. One of their samples, a 1.5 Ma basaltic andesite (VE116), is described as a flow that 'belongs to the young andesitic complex of Pico de Orizaba' (Cantagrel and Robin, 1979, p.112). Yet according to them, this sample locality is situated 50 km north of La Malinche and 110 km northwest of Pico de Orizaba! We have therefore referenced their dates in Table 1 in terms of their geographic proximity to the volcanoes of La Malinche and Cofre de Perote. Judging from the high K_2O content of their sample VE21 dated at 0.47 Ma, this most likely represents an andesite flow from Cofre de Perote; Robin and Cantagrel (1982) apparently agree with this deduction.

Although it is clear that andesitic volcanism in the northern part of the TMVB occurred between 2.6 Ma and 0.5 Ma, uncertainties in stratigraphic correlation of dated rocks mean that no rigorous constraints can be placed on the age of major andesite-dacite volcanoes such as those comprising the Cofre de Perote - Pico de Orizaba lineament. Since this chain of volcanoes morphologically resembles the Sierra Nevada - Sierra Río Frío we suggest that it evolved within the same time frame and is therefore Quaternary in age.

CONCLUSIONS AND TECTONIC IMPLICATIONS

Most of the data presented above bear on the spatial and temporal evolution of calc-alkaline volcanism in Central Mexico since the Pliocene. The modern volcanic arc is characterized by an E-W chain of large central volcanoes and monogenetic volcano fields composed predominantly of andesite and dacite. Major andesitic centers in the western part of the TMVB (*i.e.* west of the Colima graben) appear to be significantly younger than comparable volcanoes further east. K-Ar data for Tequila and Sangangüey volcanoes indicate that cone construction began between approximately 0.6 and 0.2 Ma whereas in the central part of the TMVB at Nevado de Toluca and Iztaccíhuatl in the Sierra Nevada cone growth commenced much earlier at about 1.7 Ma. Furthermore, correlations based on palaeomagnetic data and K-Ar dating in the Valley of Mexico and at its eastern margin in the Sierras Nevada and Río Frío suggest that volcanic activity since 1.7 Ma has become progressively focused at the volcanic front where the historically active Popocatépetl volcano is located. This evolutionary model may be extended to other volcanic lineaments oriented transverse to the arc, in particular Pico de Orizaba - Cofre de Perote in the east and the Colima-Cántaro chain in the west, both of which are characterized by severely eroded Quaternary volcanic rocks in the north and long-lived historically active volcanoes such as Pico de Orizaba and Volcán de Colima at the trenchward limit of arc volcanism.

In their studies of the Colima graben, Luhr and Carmichael (1980, 1981) remarked on the southward-younging character of andesitic volcanism in the Colima - Cántaro complex but suggested that the locus of volcanism had migrated southwards during the Quaternary. Our model for the Sierra Nevada adequately accounts for the apparent southward shift in the locus of volcanic activity and also explains the location of large historically active volcanoes with complex growth histories at the volcanic front. The Early Quaternary arc was initially a broad feature and in the Colima graben, for example, extended from Volcán de Colima northwards at least as far as the Cántaro complex. The focus of volcanic activity has since narrowed appreciably such that andesitic volcanism is presently concentrated at the southern extremity of the chain (Volcán de Fuego). K-Ar dates of samples collected along the crest of the chain would exhibit a southward-younging trend that could be used to substantiate a simple shift in the locus of andesitic volcanism (e.g. Allan, in press). If our analogy with the Sierra Nevada is correct, andesites and dacites similar in age to those at Cántaro (1.4 - 1.0 Ma) should be represented in the substructure of the Colima volcanoes. In monogenetic volcano fields there is a greater statistical chance of sampling younger rocks near the volcanic front. This is an important factor contributing to the southward progression of younger K-Ar dates in the Plio-Quaternary rocks of Michoacán documented earlier and the predominance of Brunhes volcanoes in the southern part of the Valley of Mexico. Since the three volcanic lineaments discussed above bound the principal areas of monogenetic volcanism, and all overlie the subducted Cocos plate, it is reasonable to apply the same evolutionary model to the entire central and eastern parts of the TMVB. However, in the western segment of the TMVB there is currently no evidence to support a similar pattern in the evolution of Quaternary volcanism.

The difference in age between major andesitic volcanoes in the western part of the TMVB and those further east appears to be directly related to the contrasting subduction regimes of the Rivera and Cocos plates which are juxtaposed beneath the Colima graben (Nixon, 1982). Although the volumes of large Quaternary volcanoes overlying the subducted portion of the Rivera plate are at least a factor of five less than the volumes of their counterparts situated above the more rapidly subducting Cocos plate, the mean eruption rates of volcanoes in the two arc segments are not radically different. For example, the eruption rate of Iztaccíhuatl between 1.7 and 0.1 Ma is estimated at 0.25 - 0.28 km^3/ka (Nixon *et al.*, in prep.). Assuming that andesites of Volcán de Tequila were erupted between 0.6 and 0.2 Ma then a probable minimum eruption rate of 0.10 km^3/ka is indicated whereas if the cone of Sangangüey was built between 0.3 and 0.2 Ma the calculated eruption rate is 0.35 km^3/ka

which is probably a maximum. The average eruption rate for major andesitic volcanoes above the Rivera plate (0.225 km^3/ka) is thus not significantly different from that calculated for volcanoes above the Cocos plate, provided that Iztaccíhuatl is representative.

One consequence of our model for the evolution of Quaternary volcanism above the subducted Cocos plate is that the volume of erupted material is greatest at the volcanic front. An exponential decrease in the volume of volcanic rocks away from the volcanic front and towards the backarc region is a characteristic feature of some West Pacific arcs (Sugimura, 1968) and it would appear that eruption rates transverse to the arc reach a maximum at the leading edge of arc volcanism. But if the TMVB is typical of modern arc environments, the greatest volume of volcanic material corresponds to the region of longest-lived activity so that across-arc eruption rates earlier in the Quaternary could be rather uniform. However, the volume of eruptive products per unit time per km of arc length appears to have diminished during this period due largely to the progressive narrowing of the active arc towards the volcanic front.

The available geologic and K-Ar data summarized above do not allow a precise estimate of the inception of calc-alkaline volcanism with an E-W trend in Central Mexico. The apparent continuity of Mio-Pliocene volcanic rocks along the modern arc is consistent with previous suggestions that the change in geometry of arc volcanism occurred after the emplacement of large volumes of Oligocene - Early Miocene ignimbrites in the NNW-SSE - trending Sierra Madre Occidental (e.g. Demant and Robin, 1975; Damon and Montesinos, 1978; Demant, 1981). Silicic ignimbrites, basalts, and andesitic lavas of Mio-Pliocene age underlie Quaternary volcanic rocks in the western part of the TMVB and occur at the northern limit of Quaternary volcanism in the central and eastern parts of the arc (Gastil *et al.*, 1978, 1979; Watkins *et al.*, 1971; Cantagrel and Robin, 1979; Demant, 1981; Allan, in press). Fieldwork and K-Ar dating in Michoacán (Demant, 1981; and this work) and at the eastern extremity of the TMVB (Cantagrel and Robin, 1979) indicate a gradual transition from Late Miocene and Pliocene lavas and pyroclastic rocks in the north to Quaternary volcanic rocks further south. The southern limit of Quaternary volcanism consistently overlies rocks of Miocene age or older. Thus a southward migration of calc-alkaline volcanism occurred in the central and eastern part of the arc between the Late Miocene or Early Pliocene and Early Quaternary. A conspicuous difference in the character of volcanic products before and after arc migration is the high proportion of siliceous pyroclastics incorporated in Late Tertiary successions, especially in

Pliocene rocks, compared to the predominance of intermediate lavas in the Quaternary volcanic province.

An intriguing similarity exists between the space-time patterns inferred above for calc-alkaline volcanism since the Miocene and the spatial distribution of Pliocene to Holocene K-rich lamprophyres in the Colima graben. Early Pliocene (4.7 - 4.2 Ma) lamprophyres were confined to the northern part of the Colima graben and later activity (3.3 - 1.15 Ma) was further restricted to the southern part of this Early Pliocene province. Late Pleistocene to Recent alkaline cones and flows overlie the trenchward limit of older lamprophyres and extend further south occurring just behind the volcanic front as defined by Volcán de Colima. Thus, K-rich alkaline volcanism in the Colima graben appears to exhibit the same general pattern of evolution as calc-alkaline volcanism associated with subduction of the Cocos plate and suggests a common causative mechanism, *viz.*, the subduction process. This inference is reinforced by the fact that alkaline and calc-alkaline volcanism has occurred simultaneously in the Colima graben since Early Pliocene.

The tectonic setting of alkaline volcanic rocks in the TMVB is currently under debate. Luhr *et al.* (1985) have proposed that alkaline volcanism in the Colima and Tepic-Chapala grabens is a manifestation of continental rifting triggered by a jump of the East Pacific ridge system into western Mexico. According to this hypothesis, the segment of East Pacific Rise bounded by the Tamayo and Rivera Fracture Zones is currently in the process of jumping eastward to the Colima graben whereupon the northwestern part of the Tepic-Chapala graben is destined to become a right-lateral transform boundary and the Colima graben the site of creation of new ocean lithosphere as a sliver of continental Mexico is transferred to the Pacific plate. The transfer process is believed to have started in the Pliocene. Our principal difficulties with this proposal stem from a number of important observations: 1) coeval lamprophyric and calc-alkaline volcanism share a similar development in time and space and the erupted volume of calc-alkaline rocks is far greater, suggesting that subduction processes are ultimately responsible; 2) lamprophyres are not found south of the trenchward limit of calc-alkaline volcanism whereas the structural integrity of the Colima graben continues south of the volcanic front for at least 80 km; and 3) listric normal faulting which characterizes regions of crustal extension such as the Basin and Range Province, for example, has been observed within the Tepic-Chapala graben but appears to be lacking in the Colima graben where subvertical deep-seated faults prevail (Allan, in press). Accordingly, we offer an alternative explanation below for the role of plate tectonic processes in the generation of alkaline and calc-alkaline volcanism in western Mexico.

Nixon (1982) recognized that the Colima graben overlies a zone of differential motion in the subducted slab created by the discrepant subduction rates of the Rivera and Cocos plates. Active rifting in this region may be explained by the interaction of this subducted transform boundary with overriding continental lithosphere. The earliest lamprophyric volcanism occurred approximately 1 Ma prior to the completion (at 3.5 Ma) of an eastward jump of the segment of East Pacific Rise between the Rivera and Orozco Fracture Zones (Mammerickx and Klitgord, 1982; Luhr *et al.*, 1985; Fig. 1). Since ridge jumps appear to take a finite amount of time to accomplish (Klitgord and Mammerickx, 1982), Early Pliocene lamprophyres in the Colima graben may herald the initial stages of differential motion between the Cocos and newly-forming Rivera plate. The beginning of extensional tectonism and alkaline volcanism in the Colima graben is approximately coincident with the opening of the Gulf of California at about 4 Ma (Larson, 1972). The Tepic-Chapala graben may represent an aborted rift or aulacogen that first began to form during 'proto-Gulf' extension concomitant with the eruption of 10 Ma basaltic lavas in the Tepic region and north of Lake Chapala. This aborted rift was reactivated during an episode of renewed crustal extension leading to the creation of the Gulf of California and concurrent with the formation of the Colima graben.

Alkaline suites in the Tepic-Chapala graben are distinguished from those in the Colima graben by their sodic affinity and Late Quaternary age, with the single exception of a hawaiite whose age is highly uncertain (basalt specimen 231 dated at 4.3 ± 1.7 (1σ) Ma by Gastil *et al.*, 1979; Table 1). Alkaline volcanic rocks near Sangangüey and Volcán Las Navajas (Fig. 2) occur furthest from the trench in a back-arc disposition analogous to the tectonic setting of other sodic suites in the circum-Pacific, notably in Japan (Kuno, 1968) and Central America (Pichler and Weyl, 1976). However, other complications may exist since alkaline suites are also developed near the termination of calc-alkaline arcs as in the case of Grenada (Arculus, 1976) and the northern Cascades north of Mount Garibaldi (Lawrence *et al.*, 1984) where their origin remains enigmatic.

The influence of Late Cenozoic plate motions on arc volcanism in Central Mexico is not well known. The E-W orientation of arc volcanism may have been initiated by major plate reorganizations recorded in East Pacific ocean lithosphere in the Late Miocene at 12.5 - 11 Ma or at 6.5 Ma (Mammerickx and Klitgord, 1982). The cause of the trenchward migration of arc volcanism which was completed by Early Quaternary is also speculative but it may have been induced by plate readjustments at 3.5 Ma or earlier (Mammerickx and Klitgord, 1982). However, the gradual focusing of andesitic volcanism towards the volcanic front in the Quaternary cannot be related to documented plate reorganizations, and occurred much too rapidly to represent a direct response to a significant change in dip of the subducted slab.

BIBLIOGRAPHY

ALLAN, J. F., Geology of the Colima and Zacoalco grabens, SW Mexico: Late Cenozoic rifting in the Mexican Volcanic Belt (in press).

ALLAN, J. F. and I. S. E. CARMICHAEL, 1984. Lamprophyric lavas in the Colima graben, SW Mexico. *Contrib. Mineral. Petrol., 88,* 203-216.

ARCULUS, R. J., 1976. Geology and geochemistry of the alkali basalt - andesite association of Grenada, Lesser Antilles island arc. *Geol. Soc. Amer. Bull., 87,* 612-624.

ARMSTRONG, R. L. and G. T. NIXON, 1980. Chemical and Sr-isotopic composition of igneous rocks from Deep Sea Drilling Project Legs 59 and 60. *In* Initial Reports of the Deep Sea Drilling Project, Washington (U. S. Govt. Printing Office), 59, 719-727.

AUBOUIN, J., J. AZEMA, J. C. CARFANTAN, A. DEMANT, C. RANGIN, and J. TOURNON, 1982. The Middle American Trench in the geological framework of Central America. *In* Initial Reports of the Deep Sea Drilling Project, Washington (U. S. Govt. Printing Office), 67, 747-755.

BLOOMFIELD, K., 1973. The age and significance of the Tenango basalt, Central Mexico. *Bull. Volcanol, 37,* 586-595.

BLOOMFIELD, K., 1975. A Late Quaternary monogenetic volcano field in Central Mexico. *Geol. Rundsch., 64,* 476-497.

BLOOMFIELD, K. and S. VALASTRO, 1974. Late Pleistocene eruptive history of Nevado de Toluca, Central Mexico. *Geol. Soc. Amer. Bull., 85,* 901-906.

BLOOMFIELD, K. and S. VALASTRO, 1977. Late Quaternary tephrochronology of Nevado de Toluca, Central Mexico. *Overseas Geol. Miner. Resour., I.G.S., 46,* 16 pp.

BURBACH, G. V., C. FROHLICH, W. D. PENNINGTON, and T. MATUMOTO, 1984. Seismicity and tectonics of the subducted Cocos plate. *J. Geophys. Res., 89,* 7719-7735.

CANTAGREL, J. M. and C. ROBIN, 1979. K-Ar dating on eastern Mexican volcanic rocks - relations between the andesitic and alkaline provinces. *Bull. Volcanol. Geotherm. Res., 5,* 99-114.

CANTAGREL, J. M., C. ROBIN, and P. VINCENT, 1981. Les grandes étapes d'évolution d'un volcan andésitique composite: exemple du Nevado de Toluca (Méxique). *Bull. Volcanol., 44,* 177-188.

CLARK, K. F., C. T. FOSTER, and P. E. DAMON, 1982. Cenozoic mineral deposits and subduction-related magmatic arc in Mexico. *Geol. Soc. Amer. Bull., 93,* 533-544.

CLOUGH, B. J., J. V. WRIGHT, and G. P. L. WALKER, 1981. An unusual bed of giant pumice in Mexico. *Nature, 289,* 49-50.

CLOUGH, B. J., J. V. WRIGHT, and G. P. L. WALKER, 1982. Morphology and dimensions of the young comendite lavas of La Primavera volcano, Mexico. *Geol. Mag., 119,* 477-485.

COCHEME, J. J. and A. DEMANT, 1982. Geologic cross-sections in the northwestern part of the Sierra Madre Occidental. *Geol. Soc. Amer., Abstracts with Programs, 14,* 156.

COLLETTA, B., 1981. Réseaux de fractures et dérive de la Basse-Californie par rapport au continent Nord-américain, *C. R. Acad. Sci. Paris, 292,* 1441-1444.

COLLETTA, B., J. ANGELIER, J. CHOROWICZ, L. ORTLIEB, and C. RANGIN, 1981. Fracturation et évolution néotectonique de la péninsule de Basse-Californie (Mexique). *C. R. Acad. Sci. Paris, 292,* 1043-1048.

COLLETTA, B. and J. ANGELIER, 1983. Tectonique cassante du nord-ouest mexicain et ouverture du Golfe de Californie. *In* Rifts et Fossés anciens, M. Popoff and J. J. Tiercelin (Eds), *Bull. Centres Rech. Explor.- Prod. Elf Aquitaine, 7,* 1, 433-441.

CORDOBA, D. A., M. TARDY, J. C. CARFANTAN, M. F. CAMPA, and C. RANGIN, 1980. Le Mexique mésogéen et le passage au système cordillerain de type Californie. Int. Geol. Congr., 26th, Paris, Colloque C5: Géologie des chaînes alpines issues de la Téthys, 18-29.

DAMON, P. E. and E. MONTESINOS, 1978. Late Cenozoic volcanism and metallogenesis over an active Benioff Zone in Chiapas, Mexico. Arizona Geol. Soc. Digest, 11, 155-168.

DAMON, P. E., M. SHAFIQUILLAH, and K. F. CLARK, 1981. Age trends of igneous activity in relation to metallogenesis in the southern Cordillera. *In* W. R. Dickinson and W. D. Payne (Eds.), Relations of tectonics to ore deposits in the southern Cordillera. *Arizona Geol. Soc. Digest, 14,* 137-154.

DEMANT, A., 1976. Contribución a la definición de las diferentes fases volcánicas y tectónicas del Eje Neovolcánico mexicano. Latinoamer. Geol. Congr. III, Acapulco. Resúmenes, 41.

DEMANT, A., 1978. Características del Eje Neovolcánico Transmexicano y sus problemas de interpretación. *UNAM, Inst. Geol. Rev. 2,* 172-187.

DEMANT, A., 1979. Vulcanología y petrografía del sector occidental del Eje Neovolcánico. *UNAM, Inst. Geol. Rev. 3,* 39-57.

DEMANT, A., 1981. L'Axe Transmexicain. Etude volcanologique et pétrographique. Sa signification géodynamique. Thèse Doct. Etat, Univ. Aix-Marseille III, 260 pp., and Appendix, 120 pp.

DEMANT, A. and J. J. COCHEME, 1983. Le volcanisme basaltique Mio-Pliocène de la frontière Sonora-Chihuahua, Sierra Madre Occidental, Mexique. *C. R. Acad. Sci. Paris, 296,* 1253-1258.

DEMANT, A. and C. ROBIN, 1975. Las fases del volcanismo en México; una síntesis en relación con la evolución geodinámica desde el Cretácico. *UNAM, Inst. Geol. Rev. 1,* 70-82.

DEMANT, A. and P. M. VINCENT, 1978. A preliminary report on the comenditic dome and ash flow complex of Sierra La Primavera, Jalisco; discussion. *UNAM, Inst. Geol. Rev., 2,* 218-222.

DEMANT, A., R. MAUVOIS, and L. SILVA MORA, 1975. Estudio geológico de las hojas Morelia y Maravatío, Estado de Michoacán. C. F. E., Inst. Geol. UNAM, unpubl. report, 30 pp.

DEMANT, A., R. MAUVOIS, and L. SILVA MORA, 1976. El Eje Neovolcánico Latinoamer. Geol. Congr. III, Acapulco. Field Guide 4, 30 pp.

DIAZ, E. C. and F. MOOSER, 1972. Formación del graben de Chapala. Sociedad Geológica Mexicana, Memoria II Convención Nacional, 144-145.

ERFFA, A. von, and W. HILGER, 1975. Geologische Karte des Gebietes von Puebla-Tlaxcala. Das Mexiko Projekt der Deutschen Forschungshemeinschaft, 1:100 000.

FERRIZ, H., 1985. Zoneamiento composicional y mineralógico en los productos eruptivos del centro volcánico de Los Humeros, Puebla, México. *Geofís. Int., 24,* Volumen Especial sobre el Cinturón Volcánico Mexicano - Parte 1 *(Ed. S. P. Verma),* 97-157.

FERRIZ, H. and C. YAÑEZ, 1981. Mapa geológico del centro volcánico de Los Humeros, estados de Puebla y Veracruz, México. Edición preliminar, Comisión Federal de Electricidad, J. de la Barrera 37, Satélite, México, 53100, México.

FRIES, C., 1960. Geología del estado de Morelos y de partes adyacentes de México y Guerrero, región central meridional de México. *UNAM, Inst. Geol. Bol. 60,* 236 pp.

GASTIL, R. G., D. KRUMMENACHER, and W. A. JENSKY, 1978. Reconnaissance geology of west-central Nayarit, Mexico. *Geol. Soc. Amer., MC 24,* 8, and map 1:200 000.

GASTIL, G., D. KRUMMENACHER, and J. MINCH, 1979. The record of Cenozoic volcanism around the Gulf of California. *Geol. Soc. Amer. Bull., 90,* 839-857.

GILL, J. B., 1981. Orogenic andesites and plate tectonics. Springer-Verlag, New York, 389 pp.

GUNN, B. M. and F. MOOSER, 1970. Geochemistry of the volcanics of Central Mexico. *Bull. Volcanol., 34,* 577-616.

HARLAND, W. B., A. V. COX, P. G. LLEWELLYN, C. A. G. PICKTON, A. G. SMITH and R. WALTERS, 1982. A geologic time scale. Cambridge University Press, Cambridge, 131 pp.

HARRIS, J. M. and I. S. E. CARMICHAEL, 1984. Siliceous volcanics around Volcán de Tequila, Jalisco, Mexico. *Geol. Soc. Amer., Abstracts with Programs, 16,* 530.

HEINE, K. and H. HEIDE-WEISE, 1973. Jungsquartäre Förderfolgen des Malinche - Vulkans und des Popocatépetl (Sierra Nevada, Mexiko) und ihre Bedeutung für die Glazialgeologie, Paläoklimatologie, und Archäologie. *Münst. Forsch. Geol. Paläont., 31-32,* 303-322.

HAUSBACK, B. P., 1982. Timing and nature of Tertiary tectonic and volcanostratigraphic events in southern Baja California, Mexico. *Geol. Soc. Amer., Abstracts with Programs, 14,* 171.

HAUSBACK, B. P., 1984. Cenozoic volcanic and tectonic evolution of Baja California Sur, Field Trip Guidebook, SEPM (Pacific Section), 39, 219-236.

HERRERO B., E. and PAL, S., 1978. Paleomagnetic study of Sierra de Chichinautzin, Mexico. *Geofís. Int., 17,* 167-180.

IRVINE, T. N. and W. R. A. BARAGAR, 1971. A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci., 8,* 523-548.

JENSKY, W. A., 1975. Reconnaissance geology and geochronology of the Bahía de Banderas area, Nayarit and Jalisco, Mexico. Unpubl. M. Sc. thesis, Univ. of California, Santa Barbara, 80 pp.

KARIG, D. E. and W. A. JENSKY, 1972. The proto-gulf of California. *Earth Planet. Sci. Lett., 17,* 169-174.

KLITGORD, K. D. and J. MAMMERICKX, 1982. Northern East Pacific Rise: magnetic anomaly and bathymetric framework. *J. Geophys. Res., 87,* 6725-6750.

KUNO, H., 1968. Differentiation of basaltic magmas. *In* Basalts, Vol. II, H. H. Hess and A. Poldervaart, (Eds.), Wiley Interscience Publ., New York, 624-688.

LAMBERT, P. W. and S. VALASTRO, 1976. Stratigraphy and age of Upper Quaternary tephras on the northwest side of Popocatépetl volcano, Mexico. *Amer. Quat. Assoc., Abstracts, 4,* 143.

LARSON, R. L., 1972. Bathymetry, magnetic anomalies, and plate tectonic history of the mouth of the Gulf of California. *Geol. Soc. Amer. Bull., 83,* 3345-3360.

LAWRENCE, R. B., R. L. ARMSTRONG, and R. G. BERMAN, 1984. Garibaldi Group volcanic rocks of the Salal Creek area, southwestern British Columbia: alkaline lavas on the fringe of the predominantly calc-alkaline Garibaldi (Cascade) volcanic arc. *J. Volcanol. Geotherm. Res., 21,* 255-276.

LUHR, J. F., 1978. Factors controlling the evolution of the prehistoric pyroclastic eruption of Volcán San Juan, Mexico. *Geol. Soc. Amer., Abstracts with Programs, 10,* 114.

LUHR, J. F. and I. S. E. CARMICHAEL, 1980. The Colima volcanic complex, Mexico. I. Post-caldera andesites from Volcán Colima. *Contrib. Mineral. Petrol., 71,* 343-372.

LUHR, J. F. and I. S. E. CARMICHAEL, 1981. The Colima volcanic complex, Mexico: Part II: Late Quaternary cinder cones. *Contrib. Mineral. Petrol., 76,* 127-147.

LUHR, J. F. and I. S. E. CARMICHAEL, 1982. The Colima volcanic complex, Mexico: III. Ash and scoria fall deposits from the upper slopes of Volcán de Colima. *Contrib. Mineral. Petrol., 80,* 262-275.

LUHR, J. F. and I. S. E. CARMICHAEL, 1985. Contemporaneous eruptions of calc-alkaline and alkaline magmas along the volcanic front of the Mexican Volcanic Belt. *Geofís. Int., 24,* Special Volume on Mexican Volcanic Belt - Part 1 *(Ed. S. P. Verma),* 203-216.

LUHR, J. F., S. A. NELSON, J. F. ALLAN, and I. S. E. CARMICHAEL, 1985. Active rifting in southwestern Mexico: manifestations of an incipient eastward spreading-ridge jump. *Geology, 13,* 54-57.

MAHOOD, G. A., 1977. A preliminary report on the comenditic dome and ash flow complex of Sierra La Primavera, Jalisco. *UNAM, Inst. Geol. Rev. 1,* 177-190.

MAHOOD, G. A., 1980. Geological evolution of a Pleistocene rhyolitic center: Sierra La Primavera, Mexico. *J. Volcanol. Geotherm. Res., 8,* 199-230.

MAHOOD, G. A., 1981. Chemical evolution of a Pleistocene rhyolitic center: Sierra La Primavera, Jalisco, Mexico. *Contrib. Mineral. Petrol., 71,* 129-149.

MAHOOD, G. A. and R. E. DRAKE, 1982. K-Ar dating young rhyolitic rocks: a case study of the Sierra La Primavera, Jalisco, Mexico. *Geol. Soc. Amer. Bull., 93,* 1232-1241.

MAMMERICKX, J. and K. D. KLITGORD, 1982. Northern East Pacific Rise: evolution from 25 m.y. B.P. to the Present. *J. Geophys. Res., 87,* 6751-6759.

MARTIN DEL POZZO, A. L., 1982. Monogenetic volcanism in Sierra Chichináutzin, Mexico. *Bull. Volcanol., 45,* 9-24.

MAUVOIS, R., A. DEMANT, and L. SILVA MORA, 1976. Estructuras terciarias en la base del Eje Neo-Volcánico (ejemplo de la depresión Tzitzio-Huetamo, Estado de Michoacán). Latinoamer. Geol. Congr. III, Acapulco, Resúmenes, 87.

McDOWELL, F. W. and S. E. CLABAUGH, 1979. Ignimbrites of the Sierra Madre Occidental and their relation to the tectonic history of western Mexico. *Geol. Soc. Amer. Spec. Paper 180,* 113-124.

McDOWELL, F. W. and R. P. KEIZER, 1977. Timing of mid-Tertiary volcanism in the Sierra Madre Occidental between Durango City and Mazatlán, México. *Geol. Soc. Amer. Bull., 88,* 1479-1487.

MOOSER, F., 1961. Los volcanes de Colima. *UNAM, Inst. Geol. Bol., 61,* 49-71.

MOOSER, F., 1972. The Mexican volcanic belt; structure and tectonics. *Geofís. Int., 12,* 55-70.

MOOSER, F., H. MEYER-ABICH, and A. R. McBIRNEY, 1958. Catalogue of active volcanoes of the world; part VI, Central America. Intern. Volc. Assoc., Napoli, Italy, 36 pp.

MOOSER, F., A. E. M. NAIRN, and J. F. W. NEGENDANK, 1974. Palaeomagnetic investigations of the Tertiary and Quaternary igneous rocks: VIII. A palaeomagnetic and petrologic study of volcanics of the Valley of Mexico. *Geol. Rundsch., 63,* 451-483.

NELSON, S. A., 1980. Geology and petrology of Volcán Ceboruco, Nayarit, Mexico. *Geol. Soc. Amer. Bull., 91,* 2290-2431.

NELSON, S. A. and I. S. E. CARMICHAEL, 1984. Pleistocene to Recent alkalic volcanism in the region of Sangangüey volcano, Nayarit, Mexico. *Contrib. Mineral. Petrol., 85,* 321-335.

NIXON, G. T., 1982. The relationship between Quaternary volcanism in Central Mexico and the seismicity and structure of subducted ocean lithosphere. *Geol. Soc. Amer. Bull., 93,* 514-523.

NIXON, G. T., R. L. ARMSTRONG and J. E. HARAKAL. The evolution of Iztaccíhuatl volcano, Central Mexico (in prep.).

ORTEGA-GUTIERREZ, F., 1978. Estratigrafía del complejo Acatlán en la Mixteca Baja, estados de Puebla y Oaxaca. *UNAM, Inst. Geol. Rev., 2,* 112-131.

PEREZ-REYNOSO, J., 1978. Geología y petrografía de la caldera de Los Humeros. *Geomimet, 3,* 91, 1-40.

PICHLER, H. and R. WEYL, 1976. Quaternary alkaline volcanic rocks in eastern Mexico and Central America. *Münster Forsch. Geol. Paläont., 38,* 159-178.

RICHTER, P. and J. F. W. NEGENDANK, 1976. Spurenelementuntersuchungen an Vulkaniten des Tales von Mexiko. *Münster Forsch. Geol. Paläont., 38-39,* 179-200.

ROBIN, C., 1982. Relations volcanologie - magmatologie - géodynamique. Application au passage entre volcanisme alcalin et andésitique dans le Sud Mexicain. Thèse Doct. Etat, Univ. Clermont, 500 pp.

ROBIN, C. and J. M. CANTAGREL, 1982. Le Pico de Orizaba (Mexique): structure et évolution d'un gran volcan andésitique complexe. *Bull. Volcanol. 45,* 299-315.

ROBIN, C., and E. NICOLAS, 1978. Particularités géochimiques de suites andésitiques mexicaines: un exemple de relations entre magmatismes alcalin et andésitique. *Bull. Soc. Géol. Fr., 20,* 193-202.

ROBIN, C.,G. CAMUS, J. M. CANTAGREL, A. GOURGAUD, P. MOSSAND, P. M. VINCENT, M. AUBERT, J. DOREL, and J. B. MURRAY, 1984. Les volcans de Colima. *Bull. PIRPSEV No. 87,* 98 pp.

SANCHEZ-RUBIO, G., 1978. The Amealco caldera. *Geol. Soc. Amer., Abstracts with Programs, 10,* 145.

SAWLAN, M. G., 1981. Episodes of volcanism in the Tres Vírgenes area, near Santa Rosalía, Central Baja California peninsula, México. *Geol. Soc. Amer., Abstracts with Programs, 13,* 104.

SAWLAN, M. G. and J. G. SMITH, 1984. Petrologic characteristics, age and tectonic setting of Neogene volcanic rocks in northern Baja California Sur, Mexico. Field Trip Guidebook, SEPM (Pacific Section), 39, 237-251.

SCHLAEPFER, C., 1968. Hoja México 14Q-h(5), con resumen de la hoja México, Distrito Federal y estados de México y Morelos. *UNAM, Inst. Geol., Carta Geol. México,* Serie de 1:100 000.

SEGERSTROM, K., 1950. Erosion studies at Paricutín, State of Michoacán, México. *U.S.G.S. Bull. 965-A,* 1-164.

STEELE, W. K., 1971. Paleomagnetic directions from the Iztaccíhuatl volcano, Mexico. *Earth Planet. Sci. Lett., 11,* 211-218.

STEELE, W. K., 1985. Paleomagnetic constraints on the volcanic history of Iztaccíhuatl. *Geofís. Int., 24,* Special Volume on Mexican Volcanic Belt - Part 1 *(Ed. S. P. Verma),* 159-167.

STEIGER, R. H. and E. JAGER, 1977. Subcomission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth Planet. Sci. Lett., 36,* 359-362.

SUGIMURA, A., 1968. Spatial relations of basaltic magmas in island arcs. *In* Basalts, Vol. II, H. H. Hess and A. Poldevaart (Eds.), Wiley Interscience Publ., New York, 537-571.

THORPE, R. S., 1977. Tectonic significance of alkaline volcanism in eastern Mexico. *Tectonophysics, 40,* 19-26.

THORPE, R. S. and P. W. FRANCIS, 1975. Volcan Ceboruco - a major composite volcano of the Mexican volcanic belt. *Bull. Volcanol., 39,* 201-213.

URRUTIA, J. F. and S. PAL, 1977. Paleomagnetic data from Tertiary igneous rocks, northeast Jalisco, Mexico. *Earth Planet. Sci. Lett., 36,* 202-206.

VENEGAS, S. S., J. J. HERRERA F., and R. MACIEL F., 1985. Algunas características de la faja volcánica mexicana y sus recursos geotérmicos. *Geofís. Int., 24,* Special Volume on Mexican Volcanic Belt - Part 1 *(Ed. S. P. Verma),* 47-81.

VERMA, S. P., 1984. Alkali and alkaline earth element geochemistry of Los Humeros caldera, Puebla, Mexico. *J. Volcanol. Geotherm. Res., 20,* 21-40.

VERMA, S. P., 1985. Mexican Volcanic Belt - Part I. Geofís. Int., 24, Special Volume on Mexican Volcanic Belt - Part 1 *(Ed. S. P. Verma)*, 7-19.

VERMA, S. P., M. LOPEZ-MARTINEZ, and D. J. TERRELL, 1985. Geochemistry of Tertiary igneous rocks from Arandas-Atotonilco area, northeast Jalisco, Mexico. *Geofís. Int. 24,* Special Volume on Mexican Volcanic Belt - Part 1 *(Ed. S.P. Verma)*, 31-45.

WAITZ, P., 1920. Nubes ardientes observadas en las erupciones del Jorullo (1759), del Ceboruco (1870) y del Volcán de Colima (1913). *Mem. Soc. Cient. Antonio Alzate, México, 37,* 267-277.

WAITZ, P., 1936. Datos históricos y bibliográficos acerca del Volcán de Colima. *Mem. Soc. Cient. Antonio Alzate, México, 53,* 349-384.

WALKER, G. P. L., J. V. WRIGHT, B. J. CLOUGH, and B. BOOTH, 1981. Pyroclastic geology of the rhyolitic volcano of La Primavera, México. *Geol. Rundsch., 70,* 1100-1118.

WATKINS, N. D., B. M. GUNN, A. K. BAKSI, D. YORK, and J. ADE-HALL, 1971. Paleomagnetism, geochemistry, and potassium-argon ages of the Río Grande de Santiago volcanics, Central Mexico. *Geol. Soc. Amer. Bull., 82,* 1955-1968.

WILCOX, R. E., 1954. Petrology of the Paricutín volcano, Mexico. *U.S.G.S. Bull., 965-C,* 281-353.

WILLIAMS, H., 1950. Volcanoes of the Paricutín region, Mexico. *U.S.G.S. Bull., 965-B,* 165-279.

WRIGHT, J.V., 1981. The Río Caliente ignimbrite: analysis of a compound Intraplinian ignimbrite from a major Late Quaternary Mexican eruption. *Bull. Volcanol., 44,* 189-211.

(Received: August 22, 1985)
(Accepted: February 20, 1986)

It is recommended that reference to this paper be made as follows:

G. T. Nixon, A. Demant, R. L. Armstrong and J. E. Harakal, 1987. K-Ar and geologic data bearing on the age and evolution of the Trans-Mexican Volcanic Belt. *Geofís. Int.*, Special Volume on Mexican Volcanic Belt - Part 3A *(Ed. S. P. Verma)*, Vol. 26-1, pp. 109-158