K-Ar ages of lavas from shield volcanoes
in the Michoacan-Guanajuato volcanic field, Mexico

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RESUMEN

Se reportan edades radiométricas K-Ar para ocho volcanes escudo y un estrato-volcán pertenecientes al Campo Volcánico de Michoacán-Guanajuato, del centro de México. Las edades varían entre 0.06 Ma y 2.27 Ma, siendo más antiguos los volcanes de la parte norte que los del sur. Esta relación fue observada también en volcanes menores de la región estudiada, tales como conos cineríticos y maares: los conos cineríticos y maares de la parte norte son más antiguos que los del sur. Por otra parte, tanto los volcanes escudo como los conos cineríticos en el norte poseen el mismo rango de edad. Estos resultados sugieren que la actividad volcánica en el Campo Volcánico de Michoacán-Guanajuato migró hacia el sur en los últimos dos millones de años, probablemente como un reflejo de cambios en el movimiento de placas, o en la ubicación y geometría de la zona de subducción.

PALABRAS CLAVE: faja volcánica mexicana; Campo Volcánico de Michoacán-Guanajuato; volcanes escudo; conos cineríticos; fechamientos K-Ar; migración de volcanismo.

ABSTRACT

We present new K-Ar ages for eight shield volcanoes and one stratovolcano in the Michoacán-Guanajuato Volcanic Field of central Mexico. The ages range from 0.06 Ma to 2.27 Ma. The volcanoes in the northern part of the study area are older than those in the south. Similar age relationships exist among smaller volcanoes; the cinder cones and maars in the north are also older than those in the south. The shield volcanoes and the cinder cones in the northern part of the Michoacán-Guanajuato Volcanic Field both span a similar time range. Our results suggest that the volcanic activity in the Michoacán-Guanajuato Volcanic Field migrated southward in the last 2 m.y., probably in response to changes in plate motion, or in the geometry and location of the Wadati-Benioff zone.

KEY WORDS: Mexican Volcanic Belt; Michoacán-Guanajuato Volcanic Field; shield volcanoes; cinder cones; K-Ar ages; migration of volcanic activity.

INTRODUCTION

The Mexican Volcanic Belt (MVB) is defined by an E-W trending zone of large composite volcanoes, small monogenetic cones, and silicic volcanic centers (Fig. 1). It is related to subduction of the Cocos and Rivera plates beneath the southwestern margin of the North American plate (Nixon, 1982; Nixon *et al.*, 1987). A geological map of Mexico (López-Ramos and Sánchez-Mejorada, 1976) assigns the rocks in MVB to mid-Tertiary to Present age. In contrast to typical trench-arc systems, the MVB is not parallel to the Middle America Trench but makes an oblique counter-clockwise angle of 20° (Molnar and Sykes, 1969). Several studies have indicated that the MVB marks a major crustal discontinuity across central Mexico (Mooser, 1972; Urrutia-Fucugauchi and Böhnel, 1988; Shurbet and Cebull, 1984; Pasquaré *et al.*, 1986). In addition to the MVB, the volcanism of Mexico is represented by the eastern alkaline province of Oligocene to Quaternary age (Cantagrel and Robin, 1979), andesites and rhyolitic ignimbrites of the Sierra Madre Occidental of Oligocene to Miocene age (McDowell and Keizer, 1977),

and the Californian province (Demant and Robin, 1975). Their spatial relationships are shown in Fig. 1.

The westernmost portion of the MVB is dominated by three major rift zones of Tepic-Zacoalco (NW-SE), Colima (N-S), and Chapala (E-W) (Fig. 1). The Michoacán-Guanajuato Volcanic Field (MGVF) is located to the east of Lake Chapala, which marks the axis of the Chapala rift. The eastern continuation of the Chapala rift cuts across the northern part of the MGVF, where E-W trending fault scarps and the depressions of Lakes Cuitzeo and Yuriria are eminent.

The Michoacan-Guanajuato Volcanic Field, with an area of 40,000 km^2, contains more than 1,000 small monogenetic volcanic centers including cinder cones, lava flows, maars, and lava domes. It lacks the large composite volcanoes observed in other portions of the belt. In addition to these small volcanic centers, the volcanic field contains about 300 medium-sized volcanoes, mainly shield volcanoes of about 10 km diameter. These discharged the largest volume of magma in the area.
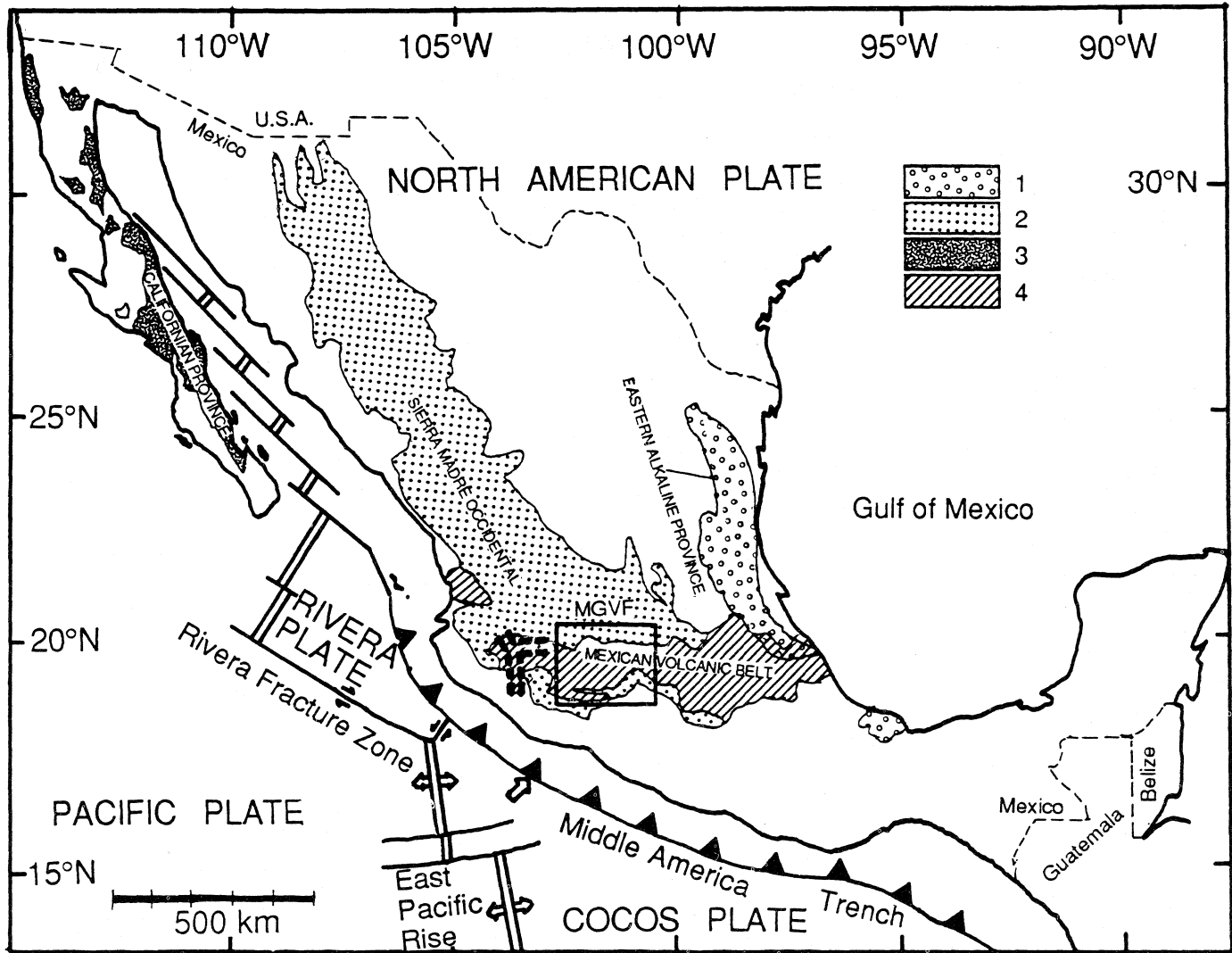
Fig. 1. Volcanic provinces of Mexico. The MGVF is shown as a rectangle. Plate boundaries are those of Drummond (1981). Intersecting double-dashed lines show three rift zones -- i.e. Tepic-Zacoalco rift (NW), Colima rift (S), Chapala rift (E) (Luhr *et al.*, 1985). Four volcanic provinces of Demant and Robin (1975) are also shown in the map. They are: 1. Eastern alkaline province (EAP), 2. Sierra Madre Occidental (SMO), 3. Californian province (CP), and 4. Mexican Volcanic Belt (MVB). The names of the provinces are partly modified.

Two cinder and lava cones of the MGVF erupted in historical times; Jorullo and Paricutín. Six cinder cones were dated by the ^{14}C method in the range 3,800-29,000 y.b.p. by Hasenaka and Carmichael (1985), and 71 more cinder cones are thought to have originated in this same time range because they have lava flows with morphologies similar to those of the dated cones (Hasenaka and Carmichael, 1985).

In this paper we analyze the spatial and temporal variations of the volcanic activity in the MGVF based on new K-Ar ages for eight shield volcanoes and one stratovolcano (Table 2) as well as previously published ^{14}C ages (Table 1).

The small and medium-sized volcanic centers have similar and overlapping distribution patterns within the study area (Hasenaka, in preparation). In the northern part of the volcanic field, however, medium-sized volcanoes are more frequent than small ones. Geomorphologically, the cinder cones in the north are older than those in the south (Hasenaka and Carmichael, 1985) which suggests a southwest migration of the volcanic activity. One of the purposes of the present study was to make a series of age determinations on medium-sized volcanoes at different distances from the trench in order to test the migration hypothesis for medium-sized volcanoes.

Small monogenetic volcanoes are typically located between medium-sized volcanic centers, either on their lower

Table 1

Compiled K-Ar and ^{14}C ages of shield volcanoes and cinder cones in the MGVF

Sample No.	Name of Volcanoes	Latitude(N)	Longitude(W)	Rock Type	Volcano Type	Method	Age Ma	Ref.
909	C.Paracho	19°35'21"	102°02'28"	Andesite	S.H.	K-Ar GM conc.	0.06±0.01	1
929	C.Buenavista Tomatlan	19°09'22"	102°36'31"	Andesite	S.H.	K-Ar GM conc.	0.54±0.08	1
974	C.Yahuarato	19°36'53"	101°33'06"	Andesite	S.H.	K-Ar GM conc.	0.54±0.07	1
978	Brinco del Diablo	19°56'21"	101°43'55"	Andesite	S.H.	K-Ar GM conc.	1.88±0.24	1
988	West of C.El Picacho	19°50'20"	101°58'01"	Andesite	S.H.	K-Ar GM conc.	0.17±0.03	1
995	C.Culiacán	20°20'16"	100°58'11"	Andesite	S.H.	K-Ar GM conc.	2.10±0.24	1
997	C.Grande	20°25'23"	100°52'35"	Andesite	S.H.	K-Ar GM conc.	2.27±0.27	1
999	C.Camatarán	20°10'37"	101°33'30"	Andesite	S.H.	K-Ar GM conc.	1.17±0.14	1
1023	C.Tancítaro	19°16'34"	102°24'57"	Andesite	S.V.	K-Ar GM conc.	0.53±0.06	1
—	C.El Metate	19°32'20"	101°59'33"	Andesite	S.H.	14C	0.0047±0.0002	2
—	C.Pelón	19°17'52"	101°54'47"	Basalt	C.	K-Ar WR	0.37±0.05	2
—	Santa Teresa	20°29'50"	100°59'53"	Basalt	C.	K-Ar WR	2.78±0.07	2
—	San Nicolás	20°23'17"	101°15'25"	Andesite	Maar	K-Ar WR	1.2	3
340	C.Sanambo	19°38'58"	101°26'32"	Andesite	S.H.	K-Ar WR	0.87±0.05	4
706	C.Grande La Piedad	20°18'10"	102°07'01"	Andesite	S.H.	K-Ar WR	1.60±0.10	4
881	C.Alto	19°59'18"	102°30'34"	Andesite	S.H.	K-Ar WR	2.60±0.10	4
Mex211	San Joaquin Jaripeo	19°51'00"	100°44'50"	Bas.-Andesite	S.H.	K-Ar WR	0.75±0.15	5

Cin volcano name is Cerro (= hill). Volcano type: SH = shield volcano, SV = stratovolcano, C = cinder or lava cone. WR = whole rock. GM conc. = groundmass concentrate (see text in details). Ref.: 1 = this study, 2 = Hasenaka and Carmichael (1985), 3 = Murphy and Carmichael (1984). 4 = Nixon *et al.* (1987), 5. Ferrari *et al.* (1990)

Table 2

New K-Ar ages of lavas from eight shield volcanoes and one stratovolcano in the MGVF.

Sample No.	Name of Volcanoes	K wt%	36Ar x10^{-10} cc/g	38Ar/36Ar	40Ar/36Ar	rad40Ar x10^{-8} cc/g	Age Ma	A.C. %
909	C.Paracho	2.05±1.00	1.41 ± 0.2	0.188±0.003	329.6±3.0	0.48 ± 0.06	0.06±0.01	89.6
929	C.Buenavista Tomatlan	0.84±0.04	6.67 ± 0.8	0.191±0.003	322.1±2.3	1.77 ± 0.23	0.54±0.08	91.7
974	C.Yahuarato	1.61±0.08	2.50 ± 0.3	0.188±0.003	430.9±3.8	3.38 ± 0.39	0.54±0.07	68.6
978	Brinco del Diablo	1.54±0.08	2.85 ± 0.3	0.187±0.003	690.9±6.7	11.3 ± 1.3	1.88±0.24	42.8
988	West of C.El Picacho	1.88±0.09	5.21 ± 0.6	0.186±0.002	319.6±2.0	1.26 ± 0.16	0.17±0.03	92.4
995	C.Culiacán	1.38±0.07	7.49 ± 0.8	0.188±0.003	446.1±2.0	11.3 ± 1.1	2.10±0.24	66.2
997	C.Grande	1.16±0.06	14.90 ± 1.5	0.187±0.002	364.5±2.2	10.2 ± 1.1	2.27±0.27	81.1
999	C.Camatarán	1.51±0.08	8.85 ± 0.9	0.188±0.003	372.8±2.2	6.84 ± 0.71	1.17±0.14	79.3
1023	C.Tancítaro	1.09±0.05	4.17 ± 0.4	0.185±0.003	348.8±1.7	2.23 ± 0.23	0.53±0.06	84.7

rad. [40]Ar = radiogenic [40]Ar. A.C. = air contamination.

flanks or in the surrounding alluvial plain. In some cases, the medium-sized volcanic centers have summit cones, either a cinder cone or a lava dome, or an alignment of small cones including one at the summit. In these cases, the cones are part of the middle-sized volcanoes. In most cases, lava flows from cinder cones on the lower flanks of medium-sized volcanic centers are geomorphologically much younger than the volcanoes themselves. They show clearly preserved pressure ridges and flow margins, and discrete flow units can be distinguished. In contrast, the lava surfaces of the medium-sized volcanoes are deeply dissected and do not show distinct flow units. An exception is Metate shield volcano (4,700 y.b.p.), whose lava flows preserve original surface features and encircle several older cinder cones at the foot of the volcano. Thus we can generalize that the medium-sized volcanoes predate the smaller monogenetic cones in the study area. However, at present we have insufficient age data to support and quantify this observation. The second purpose of this study, therefore, was to determine radiometrically the difference in age between medium-sized volcanic centers and small monogenetic volcanoes occurring in the same area.

SHIELD VOLCANOES OF THE MICHOACAN-GUANAJUATO VOLCANIC FIELD

A variety of volcanic forms are found among the small monogenetic volcanoes in the MGVF, as among the medium-sized volcanoes. Most of the latter have a shield shape with a diameter of about 10 km, and slope angles varying between 5° and 15°. Major form types include flat shields with slightly convex slopes, shields with a summit dome or a summit cinder cone, and shields with relatively steep slopes. On some shield volcanoes, the primary lava flow morphologies are still partly preserved, whereas others have deep gullies cut into their slopes.

Williams and McBirney (1982) defined three types of shield volcanoes: Icelandic, Hawaiian, and Galápagos shields. The medium-sized volcanoes of the MGVF mostly resemble Icelandic shields, as represented by Skjalbreidur volcano with almost uniform slopes of 7° to 8°, a basal diameter of 10 km, a height of 600 m, and a volume of about 15 km^3. Most shields in the MGVF have basal diameters between 3 and 8 km, heights between 300 and 700 m, slopes between 5° and 15°, and volumes between 1 and 10 km^3· On average, Mexican shield volcanoes are smaller in size than Icelandic shields; few medium-sized volcanoes have a diameter greater than 10 km and a volume greater than 20 km^3. On the other hand, Mexican shield volcanoes have steeper slope angles than Icelandic shields. Some may be classified as stratovolcanoes with concave slopes and are composed of lava flows alternating with pyroclastic deposits. A large eroded volcano like Tancítaro is recognized as a composite stratovolcano. However, in many cases, it is difficult to distinguish a shield volcano morphologically from a stratovolcano. Unless the contrary is very obvious from geological observations, medium-sized volcanoes are considered shield volcanoes in this study.

Many Icelandic shields were built during an essentially continuous discharge from a central vent, and thus are monogenetic volcanoes (Williams and McBirney, 1982). Shield volcanoes in the MGVF show lava flows with similar erosional stages (Hasenaka and Carmichael, 1986); thus their lavas were probably discharged during a single eruptive event.

K-Ar AGE DETERMINATIONS

Selection of samples

Among the nine MGVF samples selected for K-Ar dating, eight were lavas from shield volcanoes and one was from the stratovolcano Tancítaro (Fig. 2). The locations of
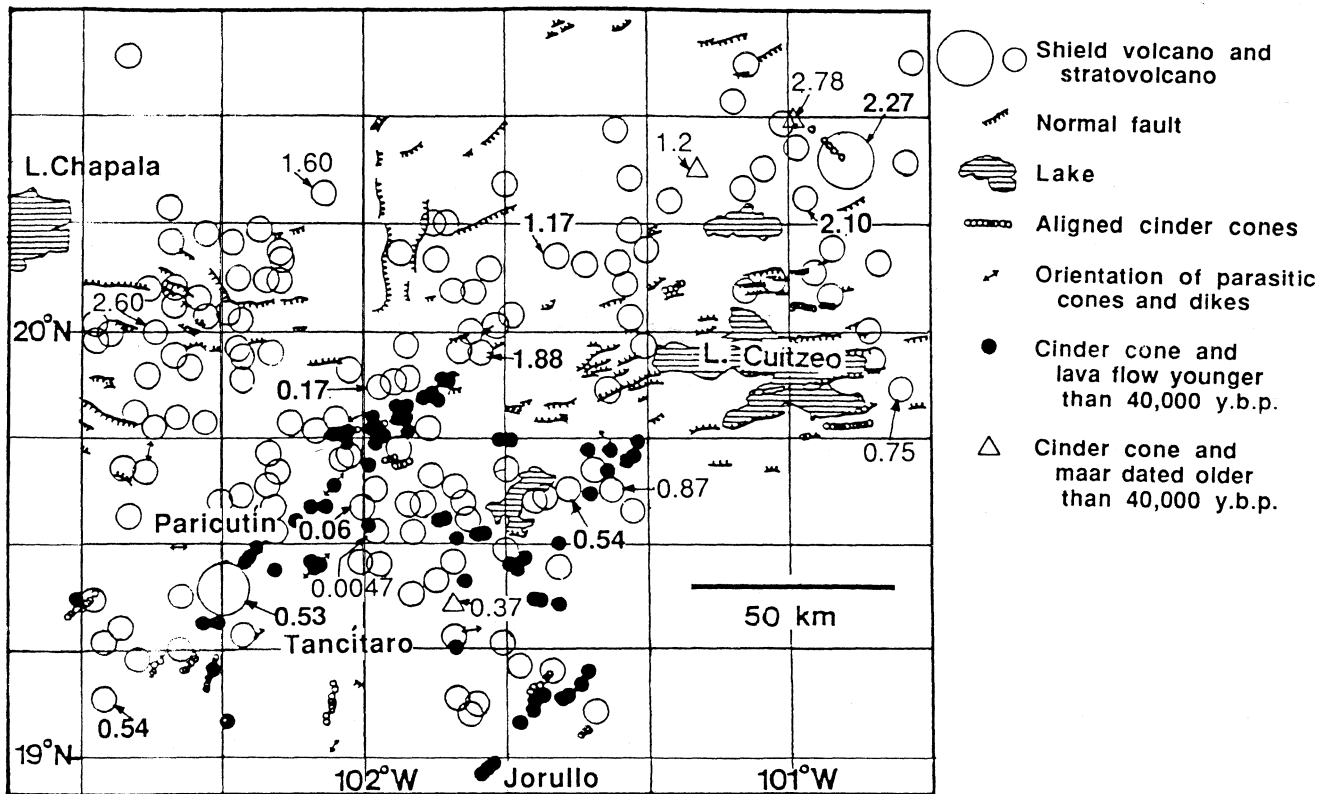

Fig. 2. Distribution of shield volcanoes and cinder cones in the MGVF and their ages. Bold numbers show K-Ar ages determined in this study. Other numbers show K-Ar ages and ^{14}C ages from Hasenaka and Carmichael (1985), Murphy and Carmichael (1984), Nixon et al. (1987), and Ferrari et al. (1990). Alignments of cinder cones, their vents and dikes, and normal faults are taken from Hasenaka and Carmichael (1985). Map area is the same as the rectangle in Fig. 1.

the summits of these volcanoes are listed in Table 1. The sampling sites were chosen so that they cover the entire area of the volcanic field; they are basically aligned in a NE-SW direction with their distances from the Middle America Trench varying from 190 km to 400 km. All the analyzed samples are calc-alkaline andesites with a limited SiO_2 range of 53 wt.% to 61 wt.% (Hasenaka, 1990). In contrast, cinder cone lavas have a wide range of composition from 47 wt.% SiO_2 to 70 wt.% SiO_2, and include both calc-alkaline and alkaline types (Hasenaka and Carmichael, 1987). Analyzed samples are all free from alteration, with phenocryst assemblages of plagioclase, ±olivine, ±augite, ±orthopyroxene, and ±hornblende in generally intersertal groundmass.

Analytical procedures

K-Ar analysis was carried out at the Department of Earth Sciences, Yamagata University, following the method of Takaoka et al. (1989). Their method is summarized as follows. For argon analysis, about 10 grams of each rock sample were crushed in a stainless steel bowl and sieved to 42-60 mesh (355-250 microns in diameter). Adhering fine particles were removed by rising in acetone. Most of the phenocrysts were removed using a magnetic separator. About 75 vol.% of the phenocrysts can be removed by this process (Konno, 1984). A 0.5 to 1.5 gram portion of this groundmass concentrate was weighed, then wrapped in aluminium foil, and introduced into an extraction line. Argon was analyzed using a peak comparison method (Takaoka, 1976) on a 20 cm radius sector-type mass spectrometer. The decay constants of $\lambda(^{40}K) = 5.543 \times 10^{-10}$ yr^{-1} and $\lambda_e(^{40}K) = 0.581 \times 10^{-10}$ yr^{-1}, and the isotopic abundance of $^{40}K/K = 0.01167$ atom. % used for the age calculation are from Steiger and Jäger (1977).

For the determination of the potassium content, about 1 gram of the identical sample used for Ar measurement was powdered in an agate bowl. About 100 mg of this powdered sample was dissolved in hydrofluoric acid and perchloric acid. The potassium content was determined by flame photometry. Analytical procedures were repeated more than twice. Replicate analyses were reproducible within 5%.

Analytical results

Table 2 shows the results of the K-Ar age determination. The ages of the shield volcanoes vary from 2.27 Ma to 0.06 Ma. The error of young samples with high air contamination is less than 10%. $^{38}Ar/^{36}Ar$ ratios of all samples have 0.188 in their deviation; thus apparent mass fractionation was not detected. Another possible problem is excess ^{40}Ar which would be due to phenocrysts that cannot be removed. Phenocrysts in young lavas sometimes show higher $^{40}Ar/^{36}Ar$ ratios than 295.5 (Fuhrman et al., 1987). The following comparison suggests that if this problem of excess ^{40}Ar occurs, the resulting absolute age will be *slightly* young. Takaoka (1989) measured the concen-

trations of radiogenic ^{40}Ar in phenocrysts of some Quaternary lavas in northeast Japan; his results range from 0.9 x 10^{-9} cc/g to 2.5 x 10^{-8} cc/g. As the samples dated in this paper have about 30 vol.% phenocrysts, the groundmass concentrates must have about 7.5 vol.% phenocrysts. If these phenocrysts have 2.5 x 10^{-8} cc/g excess ^{40}Ar, their absolute ages will be slightly young. For example, the age for Cerro Paracho would move from 0.06 Ma to 0.04 Ma and the age for Cerro Buenavista Tomatlán from 0.54 Ma to 0.49 Ma. The ranges of these shifts are within the standard deviations of the results.

Fig. 1 shows both the locations and ages of the studied shield volcanoes, as well as ages of shield volcanoes given in Hasenaka and Carmichael (1985), Nixon et al. (1987), and Ferrari et al. (1990). Fig. 1 also shows the locations and K-Ar ages of the San Nicolás maar dated by Murphy and Carmichael (1984), and the Cerro Pelón cinder cone and a cinder cone near Santa Teresa, which is nearly totally eroded, reported by Hasenaka and Carmichael (1985).

DISCUSSION

One important result of our study is the difference in age between the volcanoes in the north (farther from the Middle America trench) and those in the south (close to the trench). All the dated volcanoes in the northern portion of the volcanic field (latitude > 19°55'), are older than 1 Ma, whereas all the dated volcanoes in the southern portion of the volcanic field are younger than 1 Ma. This relationship is observed for both shield volcanoes and small volcanic centers. Thus, from Figure 2, we can conclude that at least in the MGVF, volcanism migrated southward around 1 Ma ago. Recent volcanism is restricted to the southern part of the MGVF, as documented by Hasenaka and Carmichael's (1985) data on ^{14}C age determinations. Figure 3 shows the
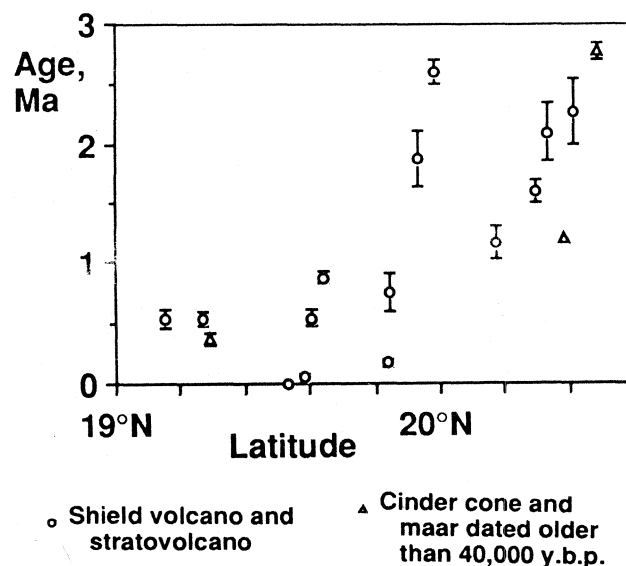

Fig. 3. Ages of shield volcanoes and cinder cones in the MGVF against their locations. Data are taken from Table 1.Vertical bars represent standard deviation of the analyses.

relationship between locations of these dated volcanoes and their ages. From this diagram we can see that the southward migration occurred rather abruptly than gradually at about 1 Ma.

There are no differences between the known ages of the shield volcanoes and of small volcanic centers in the same region (Fig. 2). Both, in the south and in the north, overlap in the same time period. It should be noted, however, that small volcanoes are among the ones with the oldest K-Ar ages in the MGVF. Cerro Pelón cinder cone (0.37 Ma) in the south has lava surface morphologies of Plv$_2$ (Hasenaka and Carmichael, 1985), i.e. the original surface features are obscured by erosion and soil development. A cinder cone near Santa Teresa (2.78 Ma) in the north is nearly totally degraded and was only recognized because of a quarry outcrop.

Direct comparison should be made between shield lavas and cinder cone lavas using the degree to which the original lava morphology is preserved. This may be difficult, as the original lava morphology might have been different to begin with. It was surprising to find the age of Cerro Paracho shield to be only 0.06 Ma, because the lava flows do not preserve such features as pressure ridges and individual lava flow units. It may be necessary to establish different criteria for calibrating ages of shield volcanoes. Also, some "shield volcanoes" may be stratovolcanoes; their slope surfaces may be covered by pyroclastic materials instead of lava flows.

CONCLUSIONS

Luhr and Carmichael (1985) pointed out a general trenchward or southwestward migration of the MVB volcanism. Colima, Popocatépetl and Citlaltépetl are all historically active composite volcanoes at the young southern limit of this volcanic chain. Cantagrel and Robin (1979) also described a southward shift of magmatism since the Pliocene through K-Ar dating. Our result confirms this general trend for an area in the central sector of the MVB. In the MGVF, the area of volcanic activity shifted about 100 km southward over the last 1 to 2 m.y. The shift was not gradual, but was rather abrupt; the northern and southern parts of this volcanic field have groups of volcanoes with different ages.

The documented southward migration probably resulted from a change in the motion of the underthrusting Cocos plate. Either the subduction dip increased, or the trench position shifted seaward. At present, there are no geophysical data to support this hypothesis, because the Wadati-Benioff zone is not well defined beneath the active volcanoes of central Mexico.

ACKNOWLEDGEMENTS

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