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Southwestward volcanic migration in the western Trans-Mexican Volcanic Belt during the last 2 Ma

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RESUMEN

Fechamientos K-Ar y resultados paleomagnéticos para la región de Chapala nos permiten estimar la edad de las rocas del Grupo Tizapán (Mioceno Tardío~Plioceno Temprano), Grupo Chapala (Mioceno Tardío~Plioceno Temprano), Grupo Travasaño (Plioceno Temprano), Grupo Grande, Grupo Palo Verde y Grupo Zacoalco (Plioceno Tardío~Pleistoceno Temprano), Grupo Santa Cruz y Grupo Acatlán (Pleistoceno Temprano). En el Campo Volcánico de Michoacán-Guanajuato (CVMG) los estudios magnetoestratigráficos permiten documentar los patrones temporales y espaciales del vulcanismo. Las características del vulcanismo en el CVMG sugieren una migración de la actividad volcánica de aproximadamente 90 km hacia la trinchera durante el período comprendido entre los Crones Brunhes y Matuyama (0.78 Ma). En la región de Chapala se observa un patrón diferente, consistente en una migración espacial transicional y de menor magnitud ocurrida entre el Plioceno y el Pleistoceno. Esta migración implica un cambio en la evolución magmática que se manifiesta en una disminución en el tamaño de los edificios volcánicos.

PALABRAS CLAVE: Faja Volcánica Trans-Mexicana, Campo Volcánico de Michoacán-Guanajuato, Rift de Chapala, edades K-Ar, paleomagnetismo, estratigrafía, magnetoestratigrafía, migración volcánica.

ABSTRACT

K-Ar dating and paleomagnetic results for the Chapala region provide age estimates for the Tizapán Group (Late Miocene~Early Pliocene), Chapala Group (Late Miocene~Early Pliocene), Travesaño Group (Early Pliocene), Grande Group, Palo Verde Group and Zacoalco Group (Late Pliocene~Early Pleistocene), Santa Cruz Group, and Acatlán Group (Early Pleistocene). For the Michoacán-Guanajuato Volcanic Field (MGVF), magnetostratigraphic studies led to an improved understanding of time and spatial patterns of volcanism. Trends of volcanism in the MGVF suggest a 90 km trenchward migration of volcanic activity around the Brunhes-Matuyama boundary (0.78 Ma). In the Chapala region a transitional and smaller spatial migration occurred around the Pliocene-Pleistocene boundary. This migration implied a change in magmatic evolution as shown by a decrease in size of volcanic edifices.

KEY WORDS: Trans-Mexican Volcanic Belt, Michoacán-Guanajuato Volcanic Field, Chapala Rift, paleomagnetism, K-Ar dates, stratigraphy, magnetostratigraphy, volcanic migration.

INTRODUCTION

The western Trans-Mexican Volcanic Belt (TMVB) features volcanic sequences which correspond closely to the regional tectonics (e.g. Delgado, 1993b). Knowledge of spatial-temporal distributions of rocks is critical for the understanding of the geological framework. The stratigraphic studies in the Chapala region, for instance (Figure 1), are essential in order to recognize events and to understand the tectonic and volcanological evolution of the region. Determination of the age of the volcanism in the Michoacán-Guanajuato Volcanic Field is also crucial for interpreting the evolution of monogenetic volcanism.

The magnetic record of volcanic rocks is usually a thermo-remanent magnetization of high stability and intensity. Stratigraphic correlations and age estimations of the rocks are possible by using the magnetic record as (a) polarity changes and excursions, and (b) directions and polar positions. This dating method is relative and needs to be calibrated by radiometric dating. The method also requires an adequate knowledge of the stratigraphic sequence to be dated.

The magnetostratigraphic method using polarity changes and excursions is useful for the Chapala region, because the sequence of the stratigraphic units (Table 1) is well known. The method offers additional information which enables one to understand complex stratigraphic relations. In this work, chronostratigraphic results are presented for the Chapala region and Michoacán-Guanajuato Volcanic Field (MGVF) in order to investigate the volcanic migration patterns.

SAMPLING AND MEASUREMENTS

In the region of the Chapala Rift (CHR), 42 paleomagnetic sites were selected to study the stratigraphic units (Figure 2). In the MGVF region 32 paleomagnetic sites were selected for 33 volcanic structures (comprising lava flows, cinder cones, shield volcanoes and one stratovolcano) along a NE-SW transect across the field (Figure 2). For each site, 5 to 17 cylindrical rock samples (2.5 cm in diameter) were obtained with a portable drilling machine. Each core had a length of 4-15 cm and was oriented using a bronze-mounted compass.

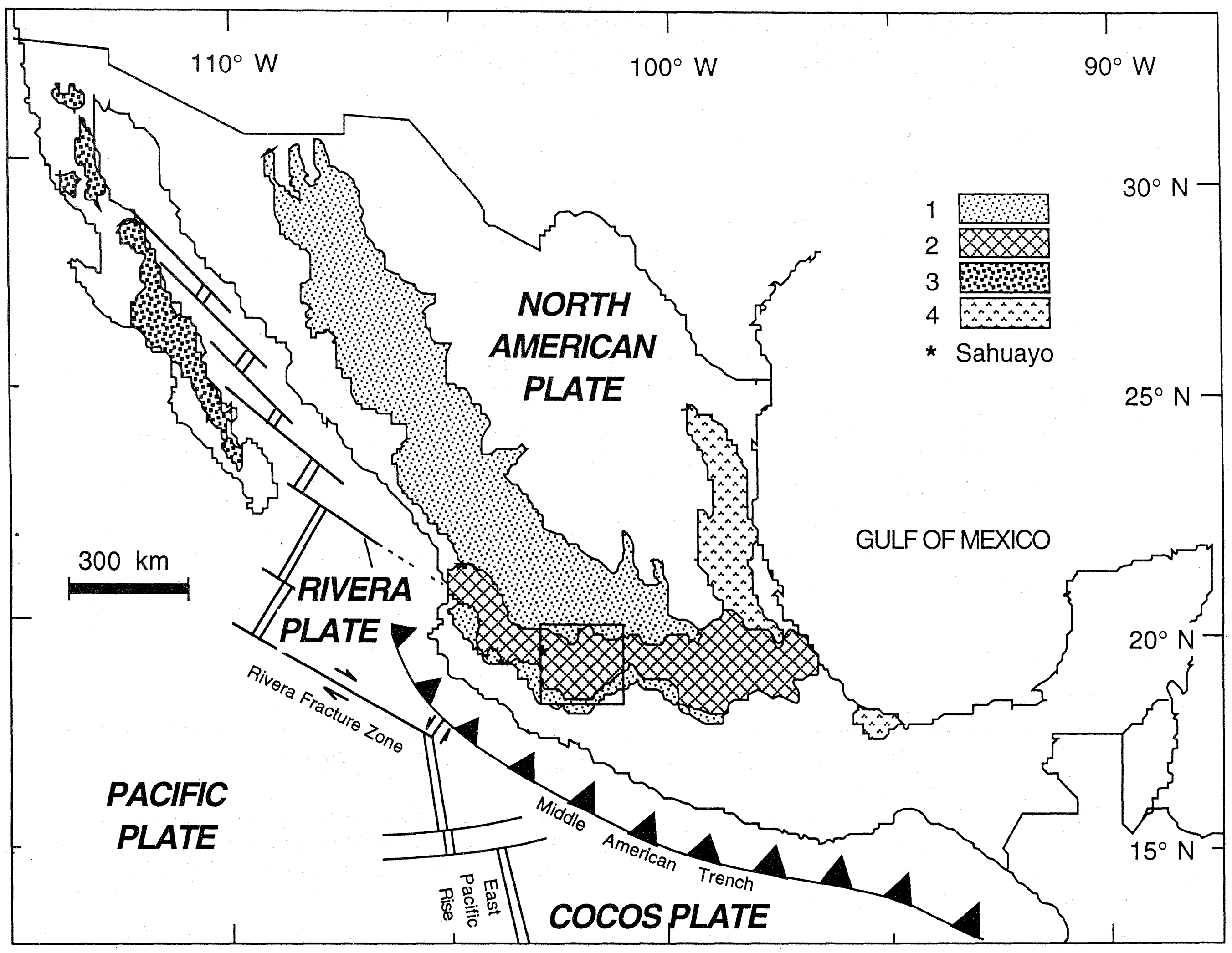


Fig. 1. Localization of the study area (small rectangle is the Chapala region and the large rectangle is the MGVF) showing the main volcanic provinces of Mexico: 1) Sierra Madre Occidental; 2) Trans-Mexican Volcanic Belt; 3) Baja Californian Province; 4) Eastern Alkaline Province. Tectonic outline from Drummond (1981).

In the laboratory, cores were cut into cylinders of 2.2 cm in length for measurements of the natural remanent magnetization (NRM) and alternating field demagnetization. Remanence was measured in a Molspin fluxgate spinner magnetometer connected to a computer provided with paleomagnetic software. The directional data were plotted on stereo nets to estimate angular dispersion of directions. Sites with small dispersion were selected for demagnetization.

Demagnetization of samples was carried out using a Schonstedt alternating field demagnetizer. First, the demagnetization behavior of a pilot sample was analyzed before proceeding to demagnetize the rest of the samples of the site. Demagnetization was carried out in steps of 2.5, 5, 20, 40, 60 and 80 mT. The demagnetization behavior of the pilot samples was analyzed on (a) stereographic equal area projection; (b) Zijderveld diagram of normalized components, and (c) normalized intensity demagnetization diagram.The data of all demagnetized samples from each site were plotted on equal-area stereo nets. The calculation of mean directions at a site was carried out using vector addition and the statistical method of Fisher (1953). Figure 3 shows the demagnetization behavior of a pilot sample from El Chiquihuitillo Formation. During demagnetization, the sample behaved stably (Figures 3a, 3b and 3c). Within-site dispersion is small as can be seen in the stereo plot of the site after demagnetization (Figure 4).

The sites with virtual geomagnetic pole (VGP) latitudes between 60° and 90°N were considered normal whereas those with VGP between 60° and 90°S were considered as reverse. Intermediate polarities were considered between 0° and 60°N (intermediate normal) and 0° and 60°S (intermediate reverse). For example, the VGP of site CHAP-671 (El Chiquihuitillo Formation) was -73.2° in latitude, thus it was taken to be reversely magnetized. For calibration of relative ages, the age ranges of polarity chrons and sub-chrons were taken from Baksi (1993), except as specified otherwise.

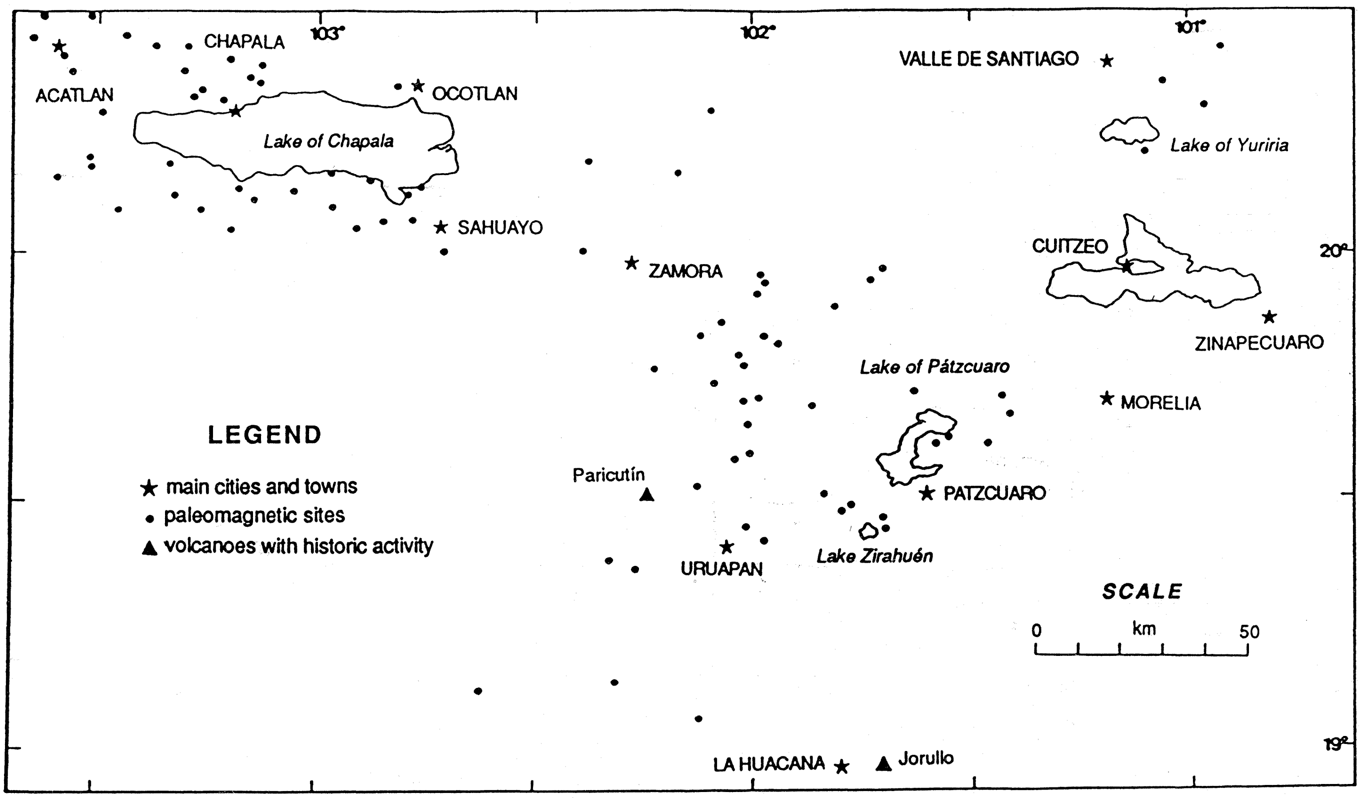


Fig. 2. Paleomagnetic sampling sites of the Chapala region and MGVF.

CHRONOSTRATIGRAPHY OF THE CHAPALA RIFT AREA

Age relationships were established by using K-Ar dates and volcanic stratigraphy (Table 2). The dating information will be published in a separate paper together with a detailed description of the stratigraphy (Delgado, in preparation).

Polarities of young volcanic rocks indicate Early Pleistocene ages (Table 3). The Santa Cruz Group is composed of andesitic and basaltic rocks erupted from monogenetic volcanoes (shield volcanoes, lava cones, and lava flows). Samples from the Totepec Andesite (CHAP-538) and El Chiquihuitillo Formation (CHAP-671) have reversed polarity, as expected from the K-Ar age of 1.4 Ma. The normal polarity of Cerro Pelón Basalt suggests an age between 1.78 Ma and 2.02 Ma (Olduvai normal subchron), based on geomorphological criteria such as the erosion of the volcanic edifice (absence of a crater rim, erosion of gullies and slope steepness), and the correlation with La Cruz Andesite and with the volcanoes of the Southern Guadalajara Volcanic Chain (SGVC) of Luhr and Lazaar (1985).

The Acatlán Group comprises dacitic and rhyolitic rocks extruded from lava domes and fissures associated to a caldera system. The Pozos Dacite has reverse polarity (Table 3) and may correspond to the Matuyama Chron (0.78 Ma-2.64 Ma). A K-Ar age of 1 Ma for these rocks (Venegas and Ruy, 1981) is in agreement with the magnetostratigraphy. The NRM of samples from the San Pedro Valencia Dacite (CHAP-666) also shows reversed polarity, which agrees with a 1 Ma K-Ar date (Table 3).

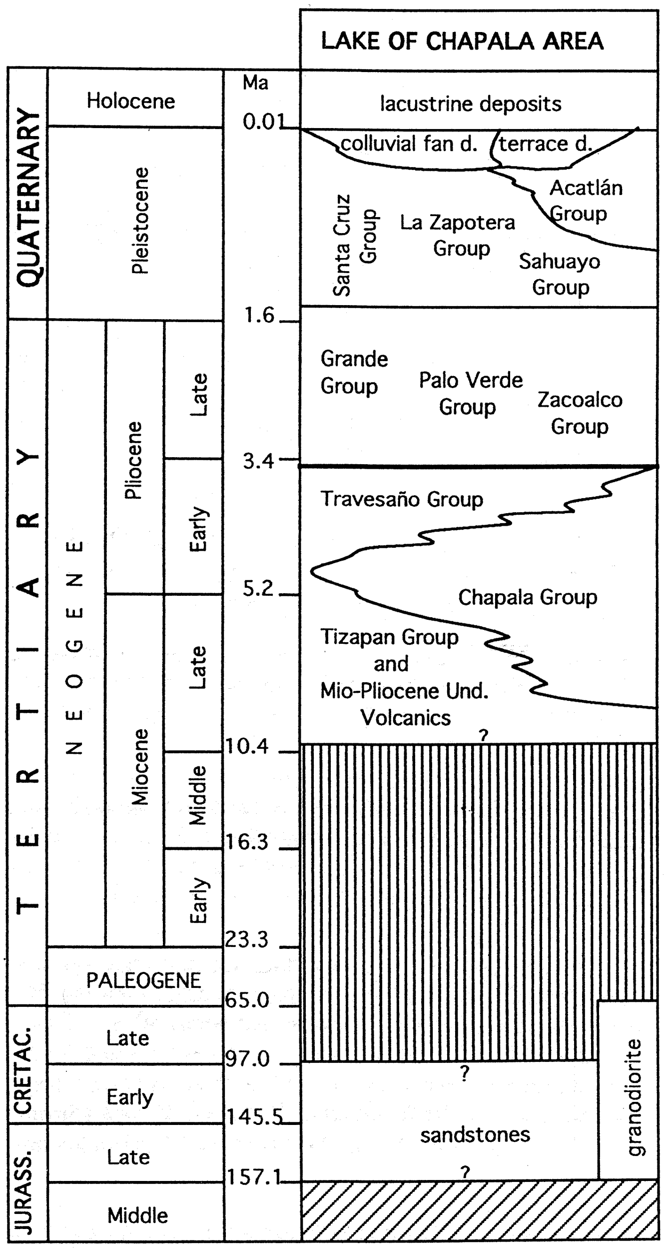
Relative ages of volcanic rocks of the Grande Group (andesites and basalts) are considered Late Pliocene~Early Pleistocene (Table 1). Stratigraphic position and polarity for El Crucero Andesite (intermediate normal) may restrict its age to the transition zone of the Olduvai Subchron around 1.78 Ma. A similar consideration can be applied to the San Francisco Andesite. The reversed polarity of Cerro García Formation was assigned to the Matuyama Chron, based on the geomorphology of the volcano and in accordance with a K-Ar age of 1.7 Ma (Table 3).

Rocks of the Travesaño Group (andesitic and basaltic lavas extruded from monogenetic volcanoes, characterized by the presence of pillows and hyaloclastic structures) are considered to be Early Pliocene. The preliminary measurements of NRM of samples from the Patomo Andesite and the Cajititlán Andesite indicate a normal polarity. Their age was constrained by stratigraphic correlations to be between the normal anomalies 3.1 and 3.2 (4.12 Ma-4.23 Ma). El Colomo Andesite (CHAP-637) has an age of about 4.17±0.05 Ma, and is assigned to the Nunivak normal Subchron. The San Marcos Andesite (4.6 Ma), which is at a lower stratigraphic level, may thus correlate with the post-Thevra reversed interval in the Gilbert Chron.

Our volcanic rocks from the Chapala Group (acidic

Table 1

Simplified stratigraphy of the Chapala region (according to Delgado 1992).



rocks and related volcano-sedimentary deposits) are assigned to the Early Pliocene. Samples of La Cañada Formation and Cerro Coronita Rhyolite show no significant variation in pole position; they have low dispersion and normal polarity. La Cañada Formation is intermediate reversely polarized, hence the age may fall in the transition zone of the Nunivak subchron (about 4.23 Ma). This interpretation agrees with K-Ar dates for the Ixtle Andesite (4.2 Ma) and the Ixtlahuacán Andesite (4.3 Ma) overlying La Cañada Formation. Gilbert *et al.* (1985) reported K-Ar ages for the Cerro Coronita Rhyolite; thus its polarity was related to the Thevra Subchron (Table 3).

The polarities obtained for the rocks of the Tizapán

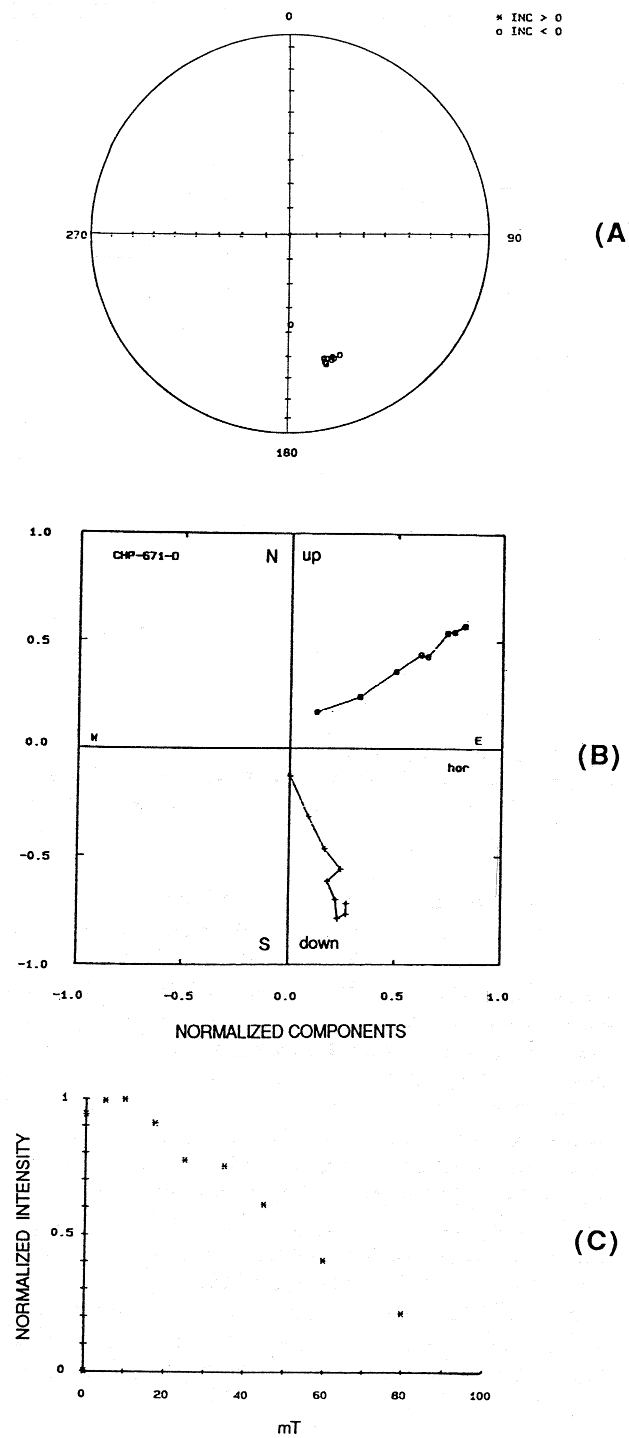


Fig. 3. Demagnetization diagrams of a pilot sample from El Chiquihuitillo Formation (CHP-671-D). A) Stereo pole projection (*: lower hemisphere; o: upper hemisphere). The pilot sample shows in this case a slight drift, probably due to a viscous component. B) Changes in direction and intensity of remanent magnetization during stepwise AF-demagnetization (Zijderveld diagram, normalized components). The sample showed a viscous component in the beginning. C) Diagram of normalized intensity versus stepwise AF values. The demagnetization of the sample was stable and the viscous component is also seen in the beginning of the process.

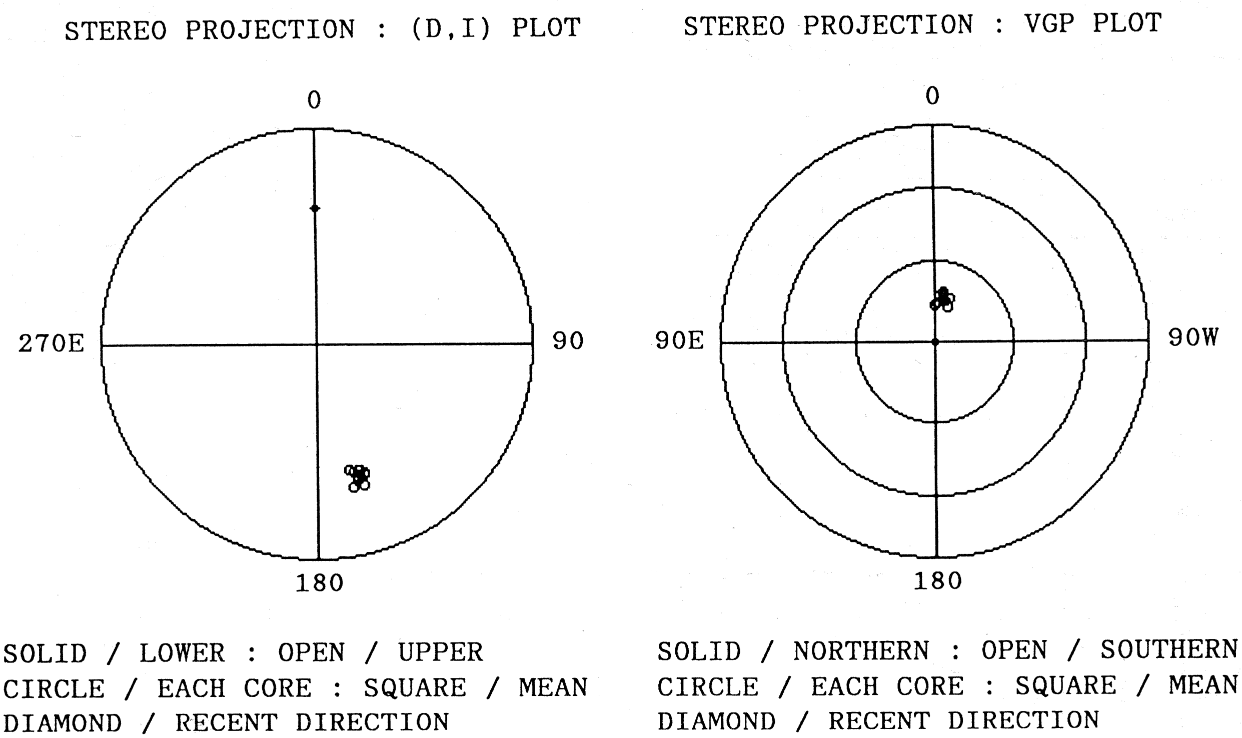


Fig. 4. Stereo projection of declination (D) and inclination (I), and stereo projection of the virtual geomagnetic pole (VGP) of all samples of the site CHAP-671 (El Chiquihuitillo Formation) after AF-demagnetization. Open circles represent each direction projected in the upper hemisphere (D, I plot) or each pole position in the southern hemisphere (VGP plot). Square represents the mean, and the diamond, the recent geomagnetic direction.

Group (the more primitive basalts in the Chapala region, and some andesites) suggest Late Miocene- Early Pliocene ages, supported by K-Ar dates and stratigraphic correlations. Correlations for intervals older than 5 Ma were not attempted, except where K-Ar ages were available. In such cases, the polarities were restricted by the ages of the closest-related magnetic anomalies. The age of Las Presitas Andesite is set at 5.8 ±1.1 Ma, based on K-Ar dates of 5.2 Ma and 6.8 Ma reported by Allan (1986); its remanence is of normal polarity. The age of the Toluquilla Basalt of 4.58 ± 1.07 Ma agrees with its normal magnetic polarity. The paleomagnetic results for Tehuantepec Andesite suggest an excursion of the magnetic field at about 10.1 Ma. The Arroyo Grande Basalt (site CHP-5) with an age between 4.37 Ma and 4.55 Ma has been correlated tentatively with polarity chron 5n.2n, because of its normal polarity and field relations. The Arroyo Grande Basalt is covered by El Ixtle Andesite lavas (4.19±0.44 Ma).

CHRONOSTRATIGRAPHY IN THE MGVF

Most volcanoes in the MGVF are Quaternary (Table 4) and magnetic polarity data are useful in order to estimate whether they are younger or older than 0.78 Ma, the boundary between Brunhes Chron and Matuyama Chron.

Results of the measurements carried out on samples from shield volcanoes, lava flows, lava cones, stratovolcanoes and cinder cones of the MGVF are summarized in Table 5 (preliminary NRM data for some sites are included). In this table, results compiled from other sources are also listed. Calibration of paleomagnetic results was carried out using the radiometric ages listed in Table 4.

The polarities of 13 sites turned out to be normal, one reversed and another of intermediate reversed polarity. The NRM of 13 additional sites was measured; 10 are of normal polarity and 3 are of reversed polarity. Some of the normal polarities were assigned to normal subchrons older than Brunhes Chron (Olduvai or Reunion), though most of the normal polarities were interpreted to be younger than 0.78 Ma.

An interesting finding was the probable identification of the Big Lost magnetic event in lavas of the MGVF. This event has been dated isotopically at 0.58 Ma (Harland *et al.*, 1990). The lavas of the Cerro Yahuarato volcano (site HKA-974) have intermediate reversed polarity with a radiometric age of 0.56 ± 0.07 Ma (Ban *et al.*, 1991). This intermediate polarity may correspond to the transition of the Big Lost magnetic event.

TRENDS OF VOLCANISM FROM MAGNETOSTRATIGRAPHY

Southward migrations of volcanism have been reported in several sectors of the TMVB. The volcanic chains Iztaccíhuatl-Popocatépetl, Sierra de Las Cruces, and Nevado

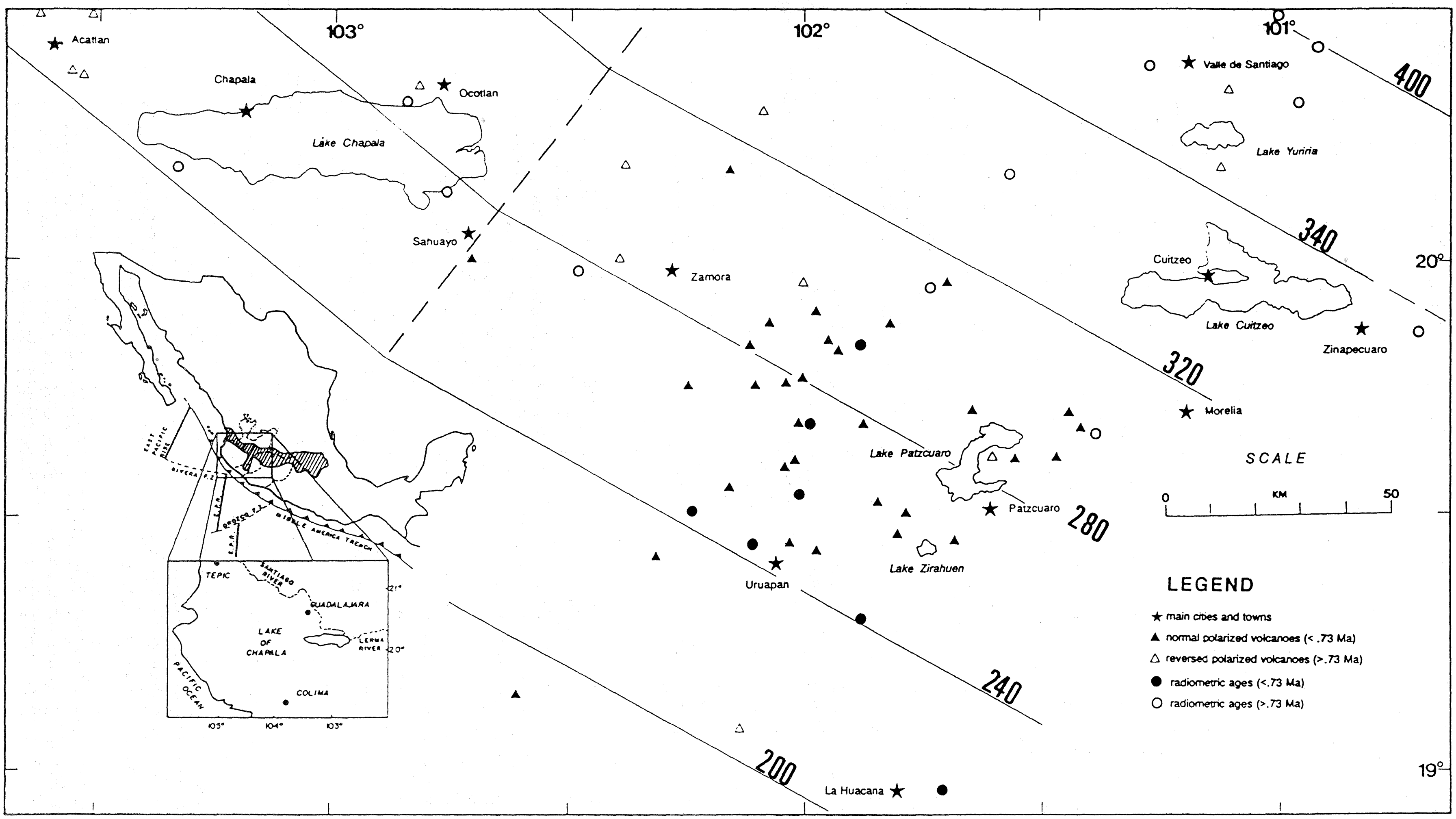


Fig. 5. Distribution of the paleomagnetic sites in the Chapala region and MGVF area, labeled according to their polarity: solid triangles indicate volcanoes younger than 0.78 Ma, whereas open triangles indicate volcanoes older than 0.78 Ma. The contour lines indicate the distance from the Middle America Trench in km. The dashed line indicates the discontinuity of the Chapala region trend and the MGVF trend.

Table 2

Paleomagnetic data for sites from the Chapala region, western Mexico. N: number of samples; P: polarity; *: normal polarity; o: reverse polarity; n: intermediate normal polarity; and r: intermediate reverse polarity. Data from Delgado (1992)

SITE	STRATIGRAPHIC UNIT GROUP	FORMATION	N	DEC	INC	K	A95	LOCATION LAT. (N)	/LON. (W)	AGE	P
CHP-538	Santa Cruz	Totepec Andesite	9	153.00	-30.34	479.24	2.35	20.49	103.52	Ma 1.39 +/- .47	r
CHP-671	La Zapotera	Chiquihuitillo Basalt	11	162.11	-35.86	744.25	1.67	20.36	102.81	Early Pleistocene	r
CHP-290	Sahuayo	La Cruz Andesite						20.14	102.75	Ma 1.29 +/- .50	
CHP-698	Sahuayo	Cerro Pelon Basalt	9	315.31	41.57	415.01	2.53	20.25	102.69	Early Pleistocene	n
CHP-636-A	Acatlan	Pozos Dacite	9	161.84	-12.77	203.26	3.61	20.36	103.57	Ma .97 +/- (?)	r
CHP-666	Acatlan	San Pedro Valencia Dacite						20.48	103.65	Ma 1.07 +/- .21	o
CHP-043-A	Grande	San Francisco Andesite	5	49.47	-43.30	12.81	22.21	20.35	103.15	Late Pliocene	r
CHP-128	Zacoalco	El Crucero Andesite	8	72.54	37.31	26.22	11.01	20.19	103.52	Late Pliocene	n
CHP-129	Zacoalco	El Rincon Basalt	7	73.91	29.21	24.92	15.59	20.21	103.52	Late Pliocene	n
CHP-722	Zacoalco	Cerro Garcia Formation						20.19	103.38	Ma 1.69 +/- .54	o?
CHP-092	Travesano	Patomo Andesite						20.45	103.44	Ma 4.19 +/- .69	*?
CHP-589	Travesano	Cajititlan Andesite						20.43	103.30	Early Pliocene	*?
CHP-014	Chapala	La Canada Formation	7	243.78	-35.74	15.71	15.71	20.36	103.26	L.Mio. - E.Plio.	r
CHP-015	Chapala	La Canada Formation	5	266.60	-60.36	14.27	20.96	20.36	103.26	L.Mio. - E.Plio.	o
CHP-062	Chapala	La Cantera Dacite	6	281.14	-52.91	4.23	36.99	20.31	103.21	L.Mio. - E.Plio.	o
CHP-684	Chapala	Cerro Coronita Rhyolite	17	321.36	37.77	111.28	3.39	20.48	102.94	L.Mio. - E.Plio.	n
CHP-005	Tizapan	Arroyo Grande Basalt						20.36	103.33	Late Pliocene	*?
CHP-106	Tizapan	San Marcos Andesite						20.33	103.53	Ma 4.64 +/- .68	
CHP-113	Tizapan	Las Presitas Andesite	9	312.10	53.96	74.72	5.99	20.20	103.56	Ma 5.17 +/- .82	n
CHP-552	Tizapan	Teocuitatlan Andesite	8	330.52	38.90	49.24	7.97	20.11	103.37	Ma 5.45 +/- .85	*
CHP-637	Tizapan	El Colomo Andesite						20.41	103.60	Late Pliocene	*?
CHP-701	Tizapan	Colorin Andesite						20.12	102.81	L.Mio. - E.Plio.	*?
CHP-705	Tizapan	Toluquilla Basalt	5	279.40	46.20	6.52	32.4	20.01	103.24	Ma 4.58 +/- 1.07	*
CHP-711	Tizapan	Tehuantepec Andesite	9	163.68	6.76	242.59	3.31	20.08	103.48	Ma 10.08 +/- .8	n
CHP-718	Tizapan	Cerro Blanco Andesite	7	340.58	22.37	31.56	10.91	20.05	103.33	Late Miocene	n
CHP-726	Tizapan	Cerro La Caja Andesite						20.06	102.86	Ma 5.23 +/- .63	
CHP-727	Tizapan	Los Olivos Andesite						20.03	102.95	L.Mio. - E.Plio.	*?
CHP-169	MPUV	El Picacho Basalt	8	253.76	-10.49	58.73	7.28	20.13	103.19	Ma 4.48 +/- .69	r
CHP-236-1	MPUV	Los Coyotes Basalt						20.12	103.03	L.Mio. - E.Plio.	o?
CHP-236-2	MPUV	Los Coyotes Air Fall Tuff	6	101.69	-39.53	393.8	3.38	20.12	103.03	L.Mio. - E.Plio.	r
CHP-236-3	MPUV	Miocene Undif. Volcanics	10	37.78	-49.85	41.95	7.54	20.12	103.03	Late Miocene	o
CHP-555	MPUV	El Divisadero Basalt	7	12.99	20.76	28.35	11.53	20.06	102.96	Ma 6.26 +/- 1.21	n
CHP-697	MPUV	El Aguacate Andesite	8	345.53	4.38	301.36	3.19	20.50	102.80	Late Miocene	n
CHP-702	MPUV	Emiliano Zapata Andesite						20.17	102.98	L.Mio. - E.Plio.	*?
CHP-704	MPUV	Palos Altos Basalt	6	2.04	31.45	43.76	10.24	20.08	103.12	L.Mio. - E.Plio.	n

Table 3

The stratigraphic units of the Chapala region, dated by the paleomagnetic and K-Ar methods. Reversed polarities are in italics, *: indicates intermediate normal polarities, o: indicates intermediate reversed polarities. Numbers in parenthesis are radiometric ages in Ma. Underlined formation names are units dated by K-Ar but without paleomagnetic data. Chronostratigraphic scale according to Harland *et al.* (1990).

PERIOD	EPOCH	CHRON	SUBCHRON OR EVENT	ANOMALY	RADIO-METRIC AGE	UNIT
QUATERNARY	Late Pleistocene	BRUNHES	Laschamp		.042	
	Middle Pleistocene		Blake		.128	
			Jamaica (Biwa I)		.182	
			Levantine (Biwa II)		0.29	
			Biwa III		0.39	
			Emperor		0.46	
			Big Lost		0.58	
			Delta		0.63	
					0.73	
	Early Pleistocene	MATUYAMA	Kamikatsura		0.85	*Chiquihuitillo Basalt*
			Jaramillo		0.90	
					0.96	*Pozos Dacite (.97)*
			Cobb Mountain		1.10	*San Pedro Valencia Dacite (1.07)*
						La Cruz Andesite (1.3)
						Totepec Andesite (1.4)
					1.67	*Cerro García Formation (1.69)*
TERTIARY	Late Pliocene		Olduvai			Cerro Pelón Basalt
					1.87	* El Crucero Andesite * San Francisco Andesite El Colomo Andesite Arroyo Grande Basalt
			Reunion		2.06	
					2.09	
						* El Rincón Basalt
			"X" event		2.31	
					2.33	
					2.48	
		GAUSS				Cerro Grande Formation (2.7)
					2.92	
			Kaena		3.01	
					3.05	
			Mammoth		3.15	
					3.40	
	Early Pliocene	GILBERT	Cochiti		3.82	
					3.93	El Ixtle Andesite (4.2)
					4.06	Cajititlán Andesite
			Nunivak			Patomo Andesite (4.2); o *La Cañada Formation*
					4.20	
					4.35	Ixtlahuacán Andesite (4.3); o *La Cantera Dacite*
			Sidufjal		4.42	Cerro Coronita Rhyolite
						o *El Picacho Basalt (4.5)*
						San Marcos Andesite (4.6)
					4.72	* Toluquilla Basalt (4.6)
			Thevra			
					5.01	Las Presitas Andesite (5.1)
						Cerro La Caja Andesite (5.2)

de Colima-Volcán de Colima are examples of southward volcanic migration (e.g. Cantagrel and Robin, 1979; Demant, 1981; Luhr and Carmichael, 1985; Mora *et al.*, 1991). These examples have led Delgado *et al.*, (1993) to propose a general trenchward migration of the volcanic front of the TMVB since Late Miocene to the present. According to Delgado *et al.* (1991) this trenchward migration may have been preceded by a pre-Miocene landward migration of the volcanic belt.

The arc-trench distance contour about 280 km from the Middle America Trench (MAT) marks a clear discontinuity in age of the MGVF. In Figure 5, solid triangles represent volcanoes whith normal polarity (younger than 0.78 Ma), and open triangles indicate volcanoes with reversed polarity (older than 0.78 Ma). Radiometric ages for the region (Table 4) are also plotted. Solid circles indicate ages younger than 0.78 Ma, while open circles represent ages older than 0.78 Ma. The figure shows that the volcanoes older than 0.78 Ma are restricted to the northeastern region (northeast of the 280 km distance contour line from the MAT), and that most of the younger volcanoes are distributed in the southwestern sector (southwest of the same contour line). The oldest shield volcanoes in the field are 2.4 Ma in age (near Valle de Santiago in the northernmost sector of the volcanic field), whilst in the south, Jorullo volcano is one of the southernmost volcanoes (active in the last century).

These data suggest a trenchward migration of volcanism in the MGVF region. Southwestward migration implies a position of the volcanic front closer to the MAT (about 190 km) and migration of the volcanic field as a whole (about 90 km southwestwards). This trend of ages from magnetostratigraphy and K-Ar data agrees with the interpretation of Ban *et al.* (1991) for several volcanoes of the MGVF. Ban *et al.* (1991) concluded that migration in the MGVF occurred suddenly within the last 1 to 2 Ma.

The trend of volcanism in the Chapala region inferred from magnetostratigraphy and K-Ar dating differs from the trend of MGVF. In Figure 6, a dashed line marks the change in trend of the arc-trench distance contour line from the MAT. This line also marks a discontinuity in the age pattern identified in the MGVF. Northwest of this boundary, volcanism is younger than 0.65 Ma up to 1.7 Ma (240 km from the MAT).

Chronostratigraphic data in the Chapala region suggest an earlier migration of volcanism there than in the MGVF. Figure 6 shows the Plio-Pleistocene volcanoes (open triangles) concentrated in the northeastern sector of the region, whereas the Pleistocene volcanoes (solid triangles) are concentrated to the west. The Plio-Pleistocene volcanoes are arranged in a N 46°W trend that can be followed continuously to the northwest into the SGVC. These volcanoes are separated 30~ 50 km from the Pleistocene volcanoes. Additionally, volcanism in the western part of the Chapala region (solid triangles) is represented by lava flows, scoria cones, lava cones and less frequently by shield volcanoes. The magnetic polarities, radiometric data, and spatial distribution of the volcanoes of the Chapala region suggest a 30~50 km trenchward migration of the volcanic front in this sector around the time of the Pliocene-Pleistocene boundary. This migration was more transitional, shorter in distance and earlier than the migration sug–

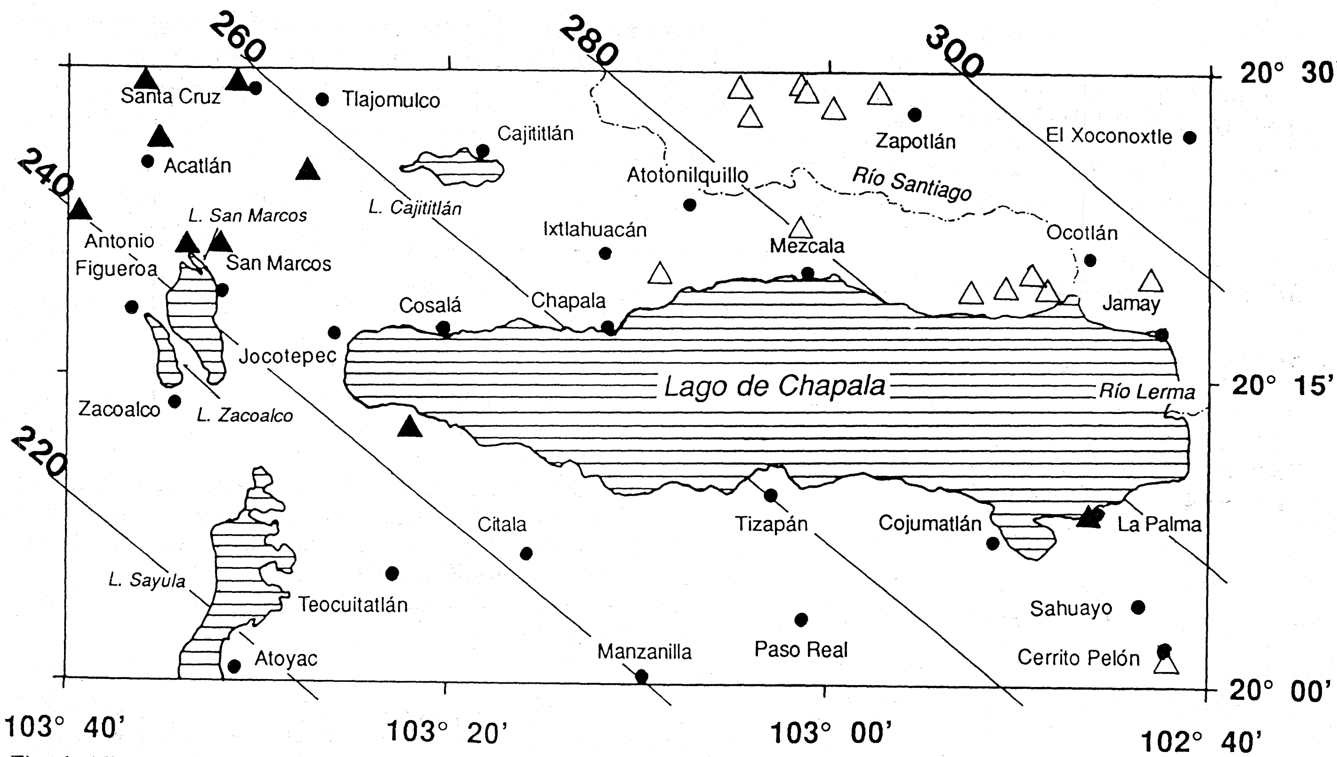


Fig. 6. Alignment of Quaternary volcanoes along a N 46°W trend. Solid triangles represent Pleistocene volcanoes, open triangles represent Late Pliocene~Early Pleistocene volcanoes. Numbers represent the distance to the Middle America Trench in km.

Table 4

Radiometric age data for volcanoes of the MGVF, Mexico.

Sample	Volcano's Name	Type	Rock Type	Method	Age (Ma)	Latitude (N)	Longitude (W)	Reference
909	Paracho	SH	A	K-Ar (WR)	0.06±0.02	19°35'21"	102°02'28"	1
929	Buena Vista	SH	A	K-Ar (WR)	0.58±0.09	19°09'22"	102°36'31"	1
974	Yahuarato	SH	A	K-Ar (WR)	0.56±0.07	19°36'53"	101°33'06"	1
978	Brinco del Diablo	SH	A	K-Ar (WR)	1.97±0.23	19°56'21"	101°43'55"	1
988	El Picacho	SH	A	K-Ar (WR)	0.18±0.03	19°50'20"	101°58'01"	1
995	Culiacan	SH	A	K-Ar (WR)	2.23±0.23	20°20'16"	101°58'11"	1
997	Grande	SH	A	K-Ar (WR)	2.35±0.25	20°25'23"	100°52'35"	1
999	Camatraran	SH	A	K-Ar (WR)	1.22±0.13	20°10'37"	101°33'30"	1
1023	Tancitaro	SV	A	K-Ar (WR)	0.55±0.06	19°16'34"	102°24'57"	1
-	Paricutin	C		HR	1943-1952	19°29'33"	102°15'04"	2
-	El Jorullo	C		HR	1759-1774	18°58'19"	101°43'03"	2
-	El Jabali	C		C14	.0038±.0001	19°26'56"	102°06'46"	2
-	El Metate	SH		C14	.0047±.0002	19°32'20"	101°59'33"	2
-	La Taza	C		C14	.0084±.0003	19°31'33"	101°43'28"	2
-	El Huanillo	C		C14	.0091±.0002	19°41'01"	101°59'04"	2
-	La Mina	C		C14	.0171±.0004	19°42'45"	101°26'02"	2
-	El Pueblito	C		C14	.0290±.0003	19°49'29"	101°55'24"	2
-	Las Cabras	C		C14	>.040	19°49'34"	101°53'37"	2
-	Pelon	C		K-Ar (WR)	0.37±0.05	19°17'52"	101°54'47"	2
-	Santa Teresa	C		K-Ar (WR)	2.78±0.07	20°29'50"	100°59'53"	2
-	San Nicolas	M		K-Ar (WR)	1.2	20°23'17"	101°15'25"	3
340	Sanambo	SH	A	K-Ar (WR)	0.87±0.05	19°38'58"	101°26'32"	4
706	Grande de La Piedad	SH	A	K-Ar (WR)	1.60±0.10	20°18'10"	102°07'01"	4
881	Alto	SH	A	K-Ar (WR)	2.60±0.10	19°59'18"	102°30'34"	4
Mex 211	San Joaquin Jaripeo	SH	BA	K-Ar (WR)	0.75±0.15	19°51'00"	100°44'50"	5

Key: A: andesite, BA: basaltic andesite, SH: shield volcano, SV: stratovolcano, C: cinder, breccia or lava cone; WR: whole rock; HR: historical record; C14: carbon 14; Ma: million years; N: north; W: west; 1: Ban *et al*, (1991); 2: Hasenaka and Carmichael, 1985; Murphy and Carmichael, 1984; Nixon *et al.*, 1987; Ferrari *et al.*, 1990.

Table 5

Paleomagnetic data of rock samples from the MGVF, western Mexico, N: number of samples; P: polarity; *: normal polarity; o: reverse polarity; and r: intermediate reversed polarity. Sites A to N were taken from Alor and Uribe (1986).

SITE	N	DEC	INC	K	A95	LOCATION LAT.(N)	LOCATION LON.(W)	AGE (Ma)	P
HKA-902	6	339.78	52.32	119.75	6.14	19.45	102.01		*
HKA-904						19.60	102.01		*?
HKA-909						19.59	102.03	0.06 +/- 0.02	*
HKA-928	11	341.22	-1.74	49.44	6.55	19.04	102.14		*
HKA-929	12	350.51	33.75	9.21	15.11	19.10	102.64	0.58 +/- 0.09	*
HKA-960B	8	344.87	30.47	39.17	8.95	19.51	102.12		*
HKA-963	11	359.07	34.68	27.32	8.89	19.70	101.99		*
HKA-964	11	39.30	27.68	27.68	8.00	19.71	102.01		*
HKA-965						19.70	101.87		*?
HKA-966						19.51	101.84		*?
HKA-967	10	340.24	36.22	18.88	11.4	19.49	101.79		*
HKA-968						19.50	101.78		*?
HKA-969						19.44	101.72		*?
HKA-972						19.61	101.58		o?
HKA-974	7	237.58	-3.27	1.44	86.45	19.63	101.55	0.56 +/- 0.07	r
HKA-975						19.73	101.64		*?
HKA-977	7	30.70	31.95	39.17	9.76	19.89	101.81		*
HKA-978	6	12.73	40.88	2.94	47.45	19.92	101.75	1.97 +/- 0.23	*
HKA-982						19.80	102.02		*?
HKA-983	9	344.28	23.49	64.17	6.47	19.85	102.07		*
HKA-984	12	184.86	-12.69	153.40	3.51	19.96	101.97		o
HKA-986						19.93	101.98		*?
HKA-988	8	335.77	37.01	29.82	10.31	19.83	101.98	0.18 +/- 0.03	*
HKA-993									o?
HKA-994									o?
HKA-1011						19.41	101.98		*?
HKA-1017						19.37	102.33		*?
HKA-1023	11	352.00	26.18	152.9	3.7	19.36	102.25	0.55 +/- 0.06	*
A	8	319.07	32.26	70.51	9.17	19.98	102.11	Late Pleistocene	*
B	8	209.90	49.43	16.15	17.18	19.76	102.01	Middle Pleistocene	*
C	8	88.93	44.60	109.99	7.32	19.82	101.91	Middle Pleistocene	*
D	8	311.41	9.81	17.23	18.96	19.95	101.69	Middle Pleistocene	*
E	8	330.94	42.64	246.51	3.53	19.71	101.42	Late Pleistocene	*
F	8	344.67	15.91	97.51	6.81	19.67	101.42	Middle Pleistocene	*
G	8	324.43	23.88	129.74	5.32	19.62	101.46	Middle Pleistocene	*
H	8	352.59	13.49	161.65	4.76	19.75	102.03	Middle Pleistocene	*
J	8	17.02	69.87	146.58	5.55	19.79	102.21	Middle Pleistocene	*
K	8	141.76	6.05	30.32	14.11	20.18	102.16	Middle Pleistocene	*
L	8	182.21	-36.73	120.51	6.12	20.32	102.11	Late Pliocene	o
M	8	174.51	-44.82	346.26	2.98	20.17	102.38	Early Pleistocene	o
N	8	310.70	-27.54	71.72	7.96	20.02	102.39	Holocene	o

gested for the MGVF, implying that the migration occurred earlier in the northwest of the volcanic arc than in the southeast. This kind of migration of volcanism has been documented for the Western North American Cordilleran arcs since the Mesozoic (Clark *et al.*, 1980, 1982; Urrutia, 1978, 1986).

Trenchward migration of volcanism could be related to a steepening of the subduction angle (Ban *et al.*, 1991; Delgado *et al.*, 1993), producing an extensional tectonic regime responsible for a highly "porous" crust that would favor the rise of slightly differentiated magmas as in most of the monogenetic volcanoes of MGVF.

CONCLUSIONS

Magnetostratigraphic studies in the Chapala region support K-Ar data as follows: Tizapán Group, Late Miocene-Early Pliocene with ages of 10.0 Ma to 4.4 Ma; Chapala Group, Late Miocene-Early Pliocene (4.9 Ma); Travesaño Group, Early Pliocene (4.1 Ma); Grande Group, Late Pliocene-Early Pleistocene (1.9 Ma to 1.6 Ma); Santa Cruz

Group and Acatlán Group, Early Pleistocene (1.7 Ma to less than 0.65 Ma). A gap of 30 km to 50 km between the Plio-Pleistocene volcanoes and the Pleistocene volcanoes suggests a transitional southwestward migration of volcanism, normal to the N 46°W trend of the Quaternary volcanoes of the Chapala region, with changing volcanological conditions evidenced by the change in size of the volcanic edifices.

The age trends obtained from magnetostratigraphic studies allow us to assign age for the volcanic rocks. These ages and the available K-Ar dates are consistent with a trenchward migration in the MGVF (Ban *et al.*, 1991) around the boundary of the Brunhes Chron and the Matuyama Chron. However, migration of volcanism in the MGVF is different than in the Chapala region. Trenchward migration at MGVF appears to have occurred suddenly at 1 to 2 Ma and over a larger distance (90 km). An additional migration of volcanism along the volcanic arc is suggested in a southeastward direction, as documented for other Cordilleran arcs.

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