Geofísica Internacional (1999), Vol., 38, Num. 4, pp. 217-230

Paleomagnetic study of the Valle de Santiago volcanics, Michoacán-Guanajuato volcanic field, Mexico

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Received: May 26, 1998; accepted: August 11, 1999.

RESUMEN

La región de Valle de Santiago del campo volcánico de Michoacán-Guanajuato está caracterizada por un lineamiento NNW-SSE de 20 maars en una zona de 50 km x 7 km, con 13 de ellos en una subzona de 14 km x 6 km. Este lineamiento parece estar asociado a una zona de debilidad cortical o fractura, orientada oblicua al patrón estructural de la Faja Volcánica Trans-Mexicana (TMVB). Ciento veintiuna muestras fueron colectadas de 13 diferentes unidades volcánicas correspondientes a andesitas pliocénicas y basaltos y andesitas cuaternarias en maars, conos cineríticos y volcanes compuestos. La polaridad magnética, excepto en una unidad, es normal. La edad de K-Ar más antigua asociada a la actividad de los maars es 1.2 Ma. Las polaridades magnéticas normales sugieren que la actividad volcánica se desarrolló predominantemente durante el crón de Brunhes, lo que indica edades más jóvenes a 0.78 Ma. La dirección media y polo paleomagnético estimada de 10 sitios son: Dec = 353.7°, Inc = 39.2°, k=42, α_{95} = 7.6° y PLAT = 78.4° N y PLOG = 180.0° E. El lineamiento de Valle de Santiago forma parte de un conjunto regional en el sector norte de la TMVB que incluye a la zona de falla de Querétaro-Taxco (QTFZ). Estos lineamientos NNW-SSE intersectan los patrones estructurales más jóvenes ENE-WSW representados por la falla Chapala-Tula. Datos paleomagnéticos para el sector este de la cuenca de Chapala indican rotaciones de bloques en sentido antihorario. Datos para el graben de Acambay en la zona de intersección con la QTFZ sugieren rotaciones en sentido horario y antihorario. Los datos para Valle de Santiago tienen una diferencia dentro de la negativa 6.3° + 6.1° con respecto a la dirección esperada. La diferencia está dentro de la incertidumbre; sin embargo, sugiere la posible ocurrencia de rotación antihoraria, similar a la deformación regional en este sector de la TMVB.

PALABRAS CLAVE: Paleomagnetismo, Valle de Santiago, Campo Volcánico Michoacán-Guanajuato, tectónica, Plio-Cuaternario.

ABSTRACT

The Valle de Santiago area of the Michoacán-Guanajuato volcanic field is characterized by a 7 km by 50 km NNW-SSE trending cluster of 20 maars, 13 in a smaller sub-area. This volcanic lineament may be associated with a pre-existing fault or zone of structural weakness, which is approximately normal to the regional structure of the Trans-Mexican volcanic belt (TMVB). One hundred and twenty one samples were collected from 13 volcanic units of Pliocene andesites and Quaternary andesites and basalts, including the maars, cinder cones and composite volcanoes. The magnetic polarity except at one site is normal. The oldest K-Ar date associated with maar volcanism is 1.2 Ma. The magnetic polarity suggests that activity took place within the Brunhes Chron, implying ages younger than 0.78 Ma. The overall mean direction and paleomagnetic pole location from 10 sites are Dec = 353.7°, Inc = 39.2°, k = 42, α_{95} = 7.6°, and PLAT = 78.4° N and PLONG = 180.0° E. The Valle de Santiago lineament forms part of a larger system in the northern part of the TMVB that includes the Querétaro-Taxco fault zone (QTFZ). These NNW-SSE trending lineaments intersect the young E-W and ENE-WSW structural trends of the TMVB, represented in the area by the Chapala-Tula fault zone. Paleomagnetic studies in the eastern Chapala basin have documented counter-clockwise (CCW) rotations. Studies in the Acambay graben close to the intersection with the QTFZ yield variable amounts of clockwise (CW) and CCW rotations. The mean declination lies to the west -6.3° + 6.1° of the expected direction, within the statistical uncertainty. Results for the Valle de Santiago area suggest a possible small CCW rotation associated with the regional compressional stress field acting on the NNW-SSE Valle de Santiago lineament and the E-W Chapala-Tula fault system.

KEY WORDS: Paleomagnetism, Valle de Santiago, Michoacan-Guanajuato volcanic field, Tectonics, Plio-Quaternary.

INTRODUCTION

The Trans-Mexican Volcanic Belt (TMVB) is a roughly east-west trending province that extends across central Mexico. It contains volcanics derived from large andesitic stratovolcanoes, silicic centers, shield volcanoes and numerous cinder cones (Figure 1). The volcanic front, marked by the active stratovolcanoes of the TMVB, is oriented some 15 degrees obliquely with respect to the Middle America trench, (Molnar and Sykes, 1969). The nature and origin of the TMVB has long been debated and the relative roles of plate subduction and crustal structure and faulting discussed (e.g.,

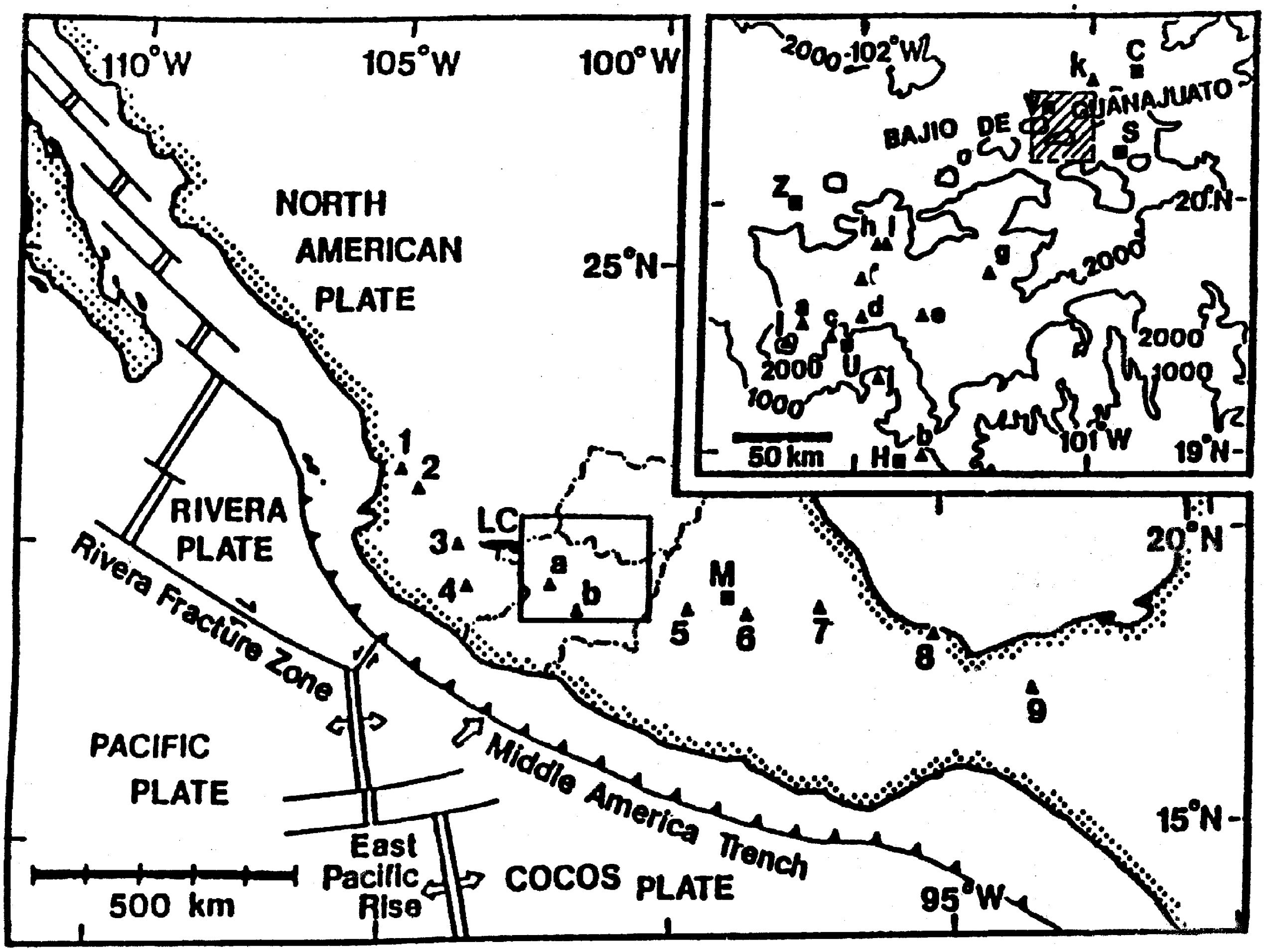


Fig. 1. Localization of the study area in the northern sector of the Michoacán-Guanajuato volcanic field (MGVF) (study area is marked by the square in the inset map). The MGVF lies in the central sector of the Trans-Mexican volcanic belt (TMVB). The TMVB extends along central Mexico and is schematically shown here by the location of several of the major volcanoes: 1, Sanganguey; 2, Ceboruco; 3, Tequila; 4, Volcán de Colima; 5, Nevado de Toluca; 6, Popocatépetl; 7, Pico de Orizaba; 8, San Martín; 9, Chichonal, a, Paricutín; and b, Jorullo. Base map adapted from Hasenaka and Carmichael (1985).

Mooser, 1972; Urrutia-Fucugauchi and Del Castillo, 1977; Pasquare *et al.*, 1988; Urrutia-Fucugauchi and Böhnel, 1988; Johnson and Harrison, 1990).

An extensive monogenetic and shield-volcano field, the Michoacán-Guanajuato volcanic field (MGVF), occupies the central sector of the TMVB. The MGVF contains more than 1000 cinder cones and shield volcanoes distributed over an area of about 40 000 km^2 (Hasenaka and Carmichael, 1985). Its southern sector contains the two new volcanoes of Paricutín (1943-1952) and Jorullo (1759-1774) (Williams, 1950; Hasenaka and Carmichael, 1985). Volcanic activity tends to get older towards the north-northeast (Delgado-Granados *et al.*, 1995). Composition of MGVF volcanoes generally ranges from basalt to basaltic andesite, being less silicic than the andesitic stratovolcanoes along the graben system of western Mexico (e.g., Ceboruco and Colima) or of the east-central TMVB (Popocatépetl and Pico de Orizaba) (Figure 1). The northeastern sector of the MGVF contains a maar volcanic field (Figure 2). Some 20 maars are distributed within an elongated 7 km by 50 km zone oriented NW-SE, with 13 maars around the town of Valle de Santiago (Ordóñez, 1906). This elongated cluster of maars has been attributed to a fault system or a deep crustal weakness zone (Murphy, 1982; Uribe-Cifuentes and Urrutia-Fucugauchi, 1992). Paleomagnetic studies may assist in identifying block rotations associated with tectonic deformation in the region. In this paper we report the initial results of a paleomagnetic study of volcanic units from maars and cinder cones of the Valle de Santiago volcanic field.

GEOLOGIC SETTING AND SAMPLING

The volcanics in the Valle de Santiago area represent the northern limit of the volcanic field of Michoacán-Guanajuato, which includes cinder cones (some 90% of the

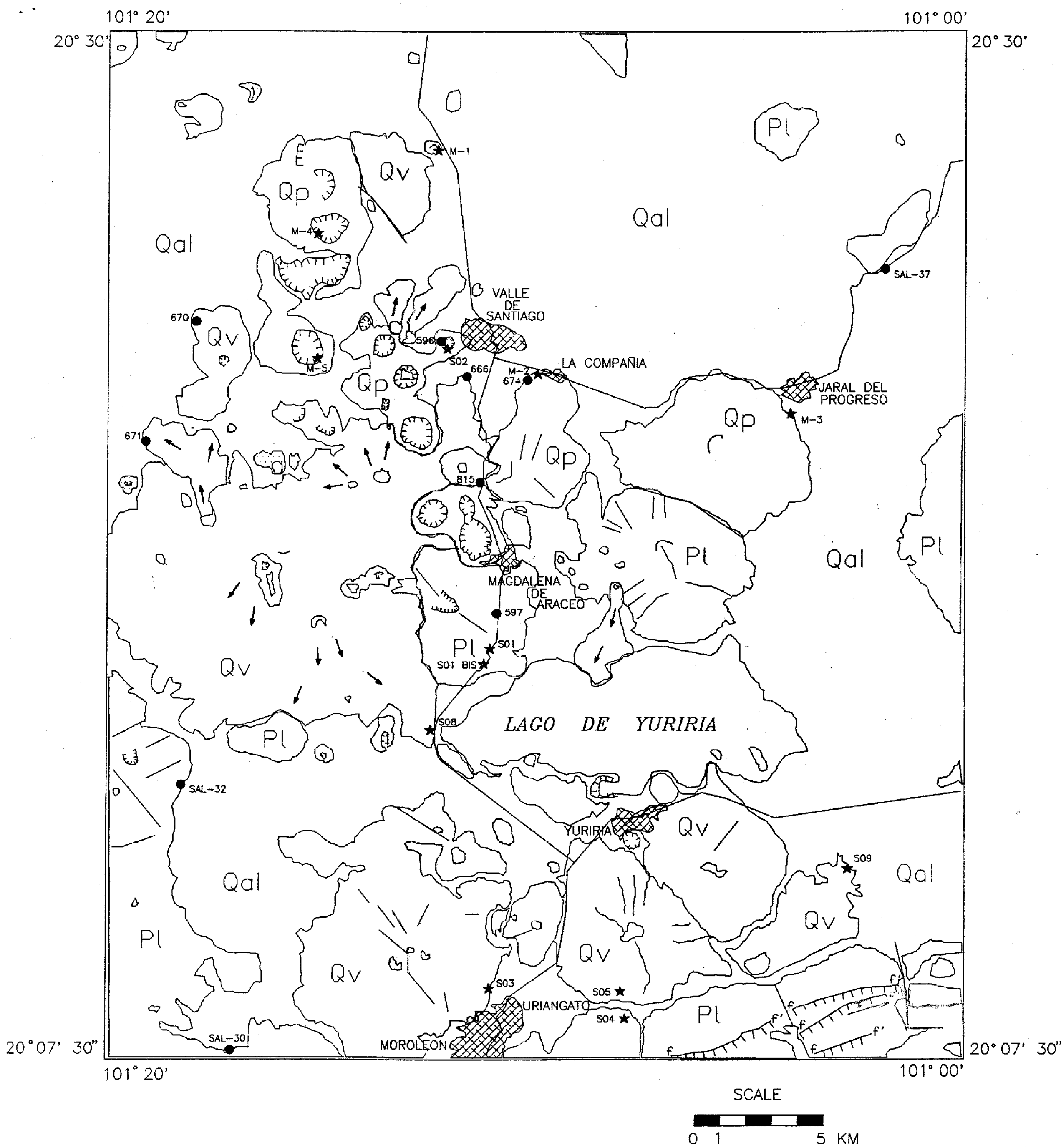


Fig. 2. Schematic geologic map of the Valle de Santiago area (modified from Silva-Mora, 1979). Location of the paleomagnetic sampling sites is indicated by the ★.

volcanic structures), lava domes, shield volcanoes, fissure lava flows, maars and tuff rings (Hasenaka and Carmichael, 1985). The Valle de Santiago area has long been studied because of the occurrence of maars and tuff rings (Ordóñez, 1906; Silva-Mora, 1979; Murphy, 1982; Uribe-Cifuentes, 1992). Murphy (1982) has proposed a preliminary chronology for the volcanic activity in the region, using K-Ar dating and volcanic stratigraphy studies. He has identified an early period of basaltic and andesitic volcanism, represented by numerous small volcanoes (e.g., Cerros Las Cuatas, El Tule, Blanco, Chapin, Guantes, Haston, and La Batea), followed by a period that includes the maars as well as several cinder cones (e.g., Cerros La Mina and Boardman). K-Ar dates for lavas of the maars range from 1.18±0.17 Ma (San Nicolás maar) to 0.073±0.024 Ma (La Alberca maar). Ban *et al.* (1992) reported K-Ar dates of 2.23±0.23 Ma and 2.35±0.25 Ma for lavas from the Cerros Culiacán and Grande, respectively. Available K-Ar dates are summarized in Table 1.

A total of 121 samples were collected from 13 sites distributed throughout the area (Figure 2). Sampling was completed in two separate field campaigns, as reflected in the site identification code used (i.e., S-01, S-02,... and M-01, M-02,...). Samples were obtained with a petrol-powered drill and non-magnetic drill bits, and oriented *in situ* by magnetic compass. Between 6 and 11 samples per site were collected. The 2.5 cm diameter cores were sliced in the laboratory into 2.5 cm long cylindrical specimens.

Units sampled include two major groups Pliocene andesites from small and medium composite volcanoes, and Quaternary andesites and basalts from composite volcanoes, maars and cinder cones (Silva Mora, 1979). Details of the sampling and petrographic observations are given in Uribe-Cifuentes (1992). Site S-01 is located some 8 km NE of Valle de Santiago along the road to Salamanca, within a blocky vesicular andesitic lava flow with scoria. Site S-01 bis is located in a similar andesitic flow, in an outcrop some 150 m to the south of S-01. Site S-02 is in the thick andesitic lava flow that forms the basal unit of La Alberca maar. Site S-03 is located on the southeastern slope of Cerro Prieto, north of

Table 1

Summary of volcanic activity in Valle de Santiago

Volcanic Chronology

	Volcanic Unit	**Age**	**Comments**
a)	Cerro Los Cuates		Period of basaltic-andesite
b)	Cerro El Tule		volcanism (248)
c)	Cerro Blanco		
d)	Cerro Chapín		
e)	Cerro Guantes	6.88 Ma	
f)	Cerro Haston		
g)	Cerro La Batea		
h)	Maar Santa Rosa		Period of maar-forming volcanism
i)	M. La Mina		
j)	C. La Mina		
k)	C. Boardman	Inception of AOB	
l)	M. Magdalena	volcanism	
m)	M. Gerónimo		
n)	M. San Nicolás	1.2 Ma.	
o)	M. Blanco		
p)	M. Laguna		
q)	M. Yuriria		
r)	M. Alvarez		
s)	M. Parangueo		
t)	M. La Cintura	.38 Ma.	
u)	Hoyita		
v)	M. Estrada	.27 Ma.	
w)	Hoyuela		
x)	Rancho Unidos Lava	.19Ma.	
y)	Paredones Lava		
z)	M. La Alberca	.073 Ma.	
1)	C. Culiacán	2.10 ± 0.24	
2)	C. Grande	2.27 ± 0.27	
3)	Santa Teresa	2.28 ± 0.07	
4)	C. Camatarán	1.17 ± 0.14	

References: (a)-(f) after Murphy (1982) and (1)-(4) after Ban *et al*. (1992)

Moroleón, within a lava flow. Site S-04 is in a lava flow on the northern slope of Cerro Jara Brava, east of Moroleón and Uriangato. Site S-05 is on the southern slope of Cerro El Capulín within an andesitic lava flow. Site S-08 is in a massive pink-gray andesitic flow from Cerro El Tule located west of Yuriria maar on the western side of the road between Salamanca and Uriangato. Site S-09 is in a basaltic lava front originating from the cinder cone of Cerro Porullo, southeast of Casacuaran. Site M-01 is located in the cinder cone of Cerro Guantecillos, 8 km south of Salamanca. Site M-02 is located in a lava flow from Cerro Los Cuates, in La Compañía, some 3 km from Valle de Santiago. Site M-03 is located in a light gray massive andesitic lava flow from Cerro La Tetilla in Jaral del Progreso, some 14 km east of Valle de Santiago. Site M-04 is in a thick lava flow within the pyroclastic sequence of Hoya Rincón de Parangueo maar. Site M-05 is in a thick lava flow within the pyroclastic sequence in the southern sector of the San Nicolas maar.

PALEOMAGNETIC STUDY

The intensity and direction of natural remanent magnetization (NRM) were measured with a Molspin fluxgate magnetometer. Most sites show normal polarity (Figure 3). Site M-01 shows reverse polarity and sites S-05 and M-05 show intermediate directions with downward inclination and easterly and westerly declinations, respectively. The NRM directions are plotted in equal-area projections (examples are given in Figure 3). Progressive alternating field (AF) demagnetization with a Schonstedt AF demagnetizer yield the vectorial composition and coercivity spectra of NRM. Maximum fields used were 100 mT. Several samples from each site were selected for detailed AF demagnetization. From the vector plots, AF fields were selected for the bulk demagnetization of the rest of samples of each site. Characteristic remanent magnetization (ChNRM) components were determined from the linear segments in the vector plots, and in some cases from remagnetization circle analysis and principal component (PCA) analysis (Zijderveld, 1967; Dunlop, 1979; Kirschvink, 1980). Examples of vector plots for several samples are included in Figure 4. Normalized intensity graphs for the AF demagnetized samples were analyzed for the coercivity spectra (Figure 5). In most cases, low coercivity minerals are the magnetic carriers of the NRM. In most cases, less than 20 % of the initial NRM intensity remains after demagnetization to fields of about 80-100 mT (Figure 5). Univectorial and multivectorial magnetizations can be documented from the vector plots. In some cases, overlapping coercivity spectra are indicated by the curved AF demagnetization paths (e.g., samples 35b and 40a; Figure 4). Examples of remagnetization circles for samples 78 and 79, and a summary of directions and circles for site M-02 are included in Figure 6.

NRM and ChNRM mean directions for each site have been calculated by giving unit weight to sample directions. The corresponding statistical parameters for the vector means are determined by Fisher statistics (Fisher, 1953). Results are summarized in Table 2. The site mean directions for ChNRM for all sites, with their corresponding confidence circle, are plotted in Figure 7. Virtual geomagnetic pole (VGP) positions are calculated assuming dipolar relationships. The overall mean direction and pole position for the volcanic units of Valle de Santiago volcanic field have been calculated by vector summation of selected site mean directions, based on eleven sites. Results for sites S-05 and M-05 showing intermediate directions with easterly or westerly declinations were not included in the overall vector mean. Statistical analysis of the angular distribution of the site means shows that these two site directions are outliers. The sites correspond to the volcanic cone of El Capulín (S-05) and the San Nicolás maar (M-05) (Figure 2). Site M-05 shows a small value of the k parameter (k=10), whereas site S-05 presents a higher value (k=100). Site M-04 on the Rincón de Parangueo maar presents high angular dispersion; deletion of this site direction from the overall mean direction calculation will reduce the angular dispersion (Table 2).

The estimated overall mean direction for the Valle de Santiago volcanics is compared with the expected direction from the northern Mexico and North America paleomagnetic data base (Table 2). The parameters for the rotation and the statistical uncertainties are from Demarest (1983). These parameters are given in terms of differences between the observed declination (D) and expected declination (De) for the rotation ($R+\Delta R$) and between the observed inclination (I) and the expected inclination (Ie) for the flattening parameter ($F+\Delta F$).

DISCUSSION

The elongated NNW-SSE distribution of the maars in the Valle de Santiago for over 50 km has been taken as evidence for a buried pre-existing fault or zone of crustal weakness (e.g., Murphy, 1982; Uribe-Cifuentes, 1992). This NNW-SSE lineament of volcanic structures contrasts with the distribution of cinder cones in the Michoacán-Guanajuato volcanic field and with the structural pattern of the region (Figure 8). Tibaldi (1989) has documented major Pleistocene faults in northern Michoacán, which present ESE-WNW orientations and generally normal or left-lateral strike-slip movements (Figure 8). The relationship between faults and maars is well documented in several volcanic provinces, but local conditions in the area of Valle de Santiago must have been important since no other maar clusters are present in the MGVF (Murphy, 1982). A fault system oriented NNW-SSE may have served as an efficient conduit for rising magma and may have controlled the groundwater flow, thus favoring the generation of phreatomagmatic eruptions (e.g., Wohletz and Sheridan, 1983).

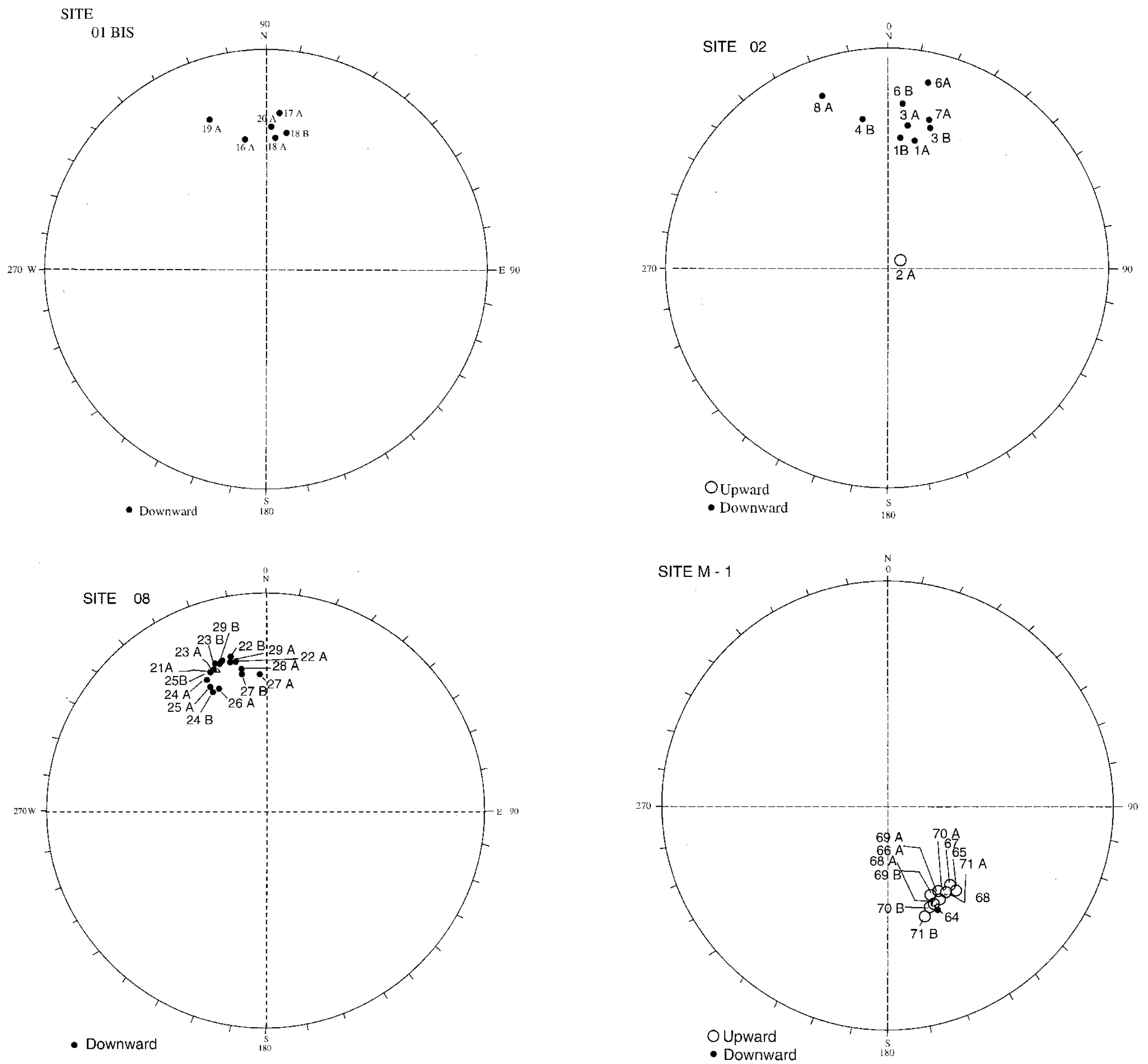


Fig. 3. Examples of NRM directional distributions for sites S-01 bis, S-02, S-08 and M-01. Directions plotted in equal-area plots. Solid symbols correspond to downward inclination (normal polarity) and open symbols correspond to upward inclination (reverse polarity).

Cinder cones in the MGVF form several clusters (Hasenaka and Carmichael, 1985; Connor, 1990). Connor (1990) showed that about 75% of the cinder cones belong to 8 clusters with 45 to 159 cones each. In the three southern clusters the cones form cone alignments some 20-50 km long with a regional orientation between 20° and 40°, parallel to the plate convergence direction. These cone alignments are oblique to the trend of regional faults, such as the Chapala-Tula system and the Oaxaca-Chapala system (Johnson and Harrison, 1990). The magmas erupted within cone alignments are high in Mg, which has been taken as evidence of rapid ascend through fractures (Hasenaka and Carmichael, 1985). Cinder cones that show spatial relations with the fault systems are generally smaller, consisting of 3 to 7 cones spaced up to 1.5 km apart in arrays parallel to the strike of the faults (Connor, 1990). Volcanic alignments are related to the stress field (Nakamura, 1977); however, the tectonic implications of the cinder cone alignments in the MGVF cannot be easily explained. The lineament of maars in the Valle de Santiago area is high-angle oblique to the regional trend of cone alignments in the southern MGVF and to the plate convergence direction. It is approximately normal to the trend of the Chapala-Tula fault system. Connor (1990) has stressed that the distribution of cinder cones, shield volcanoes and strato-

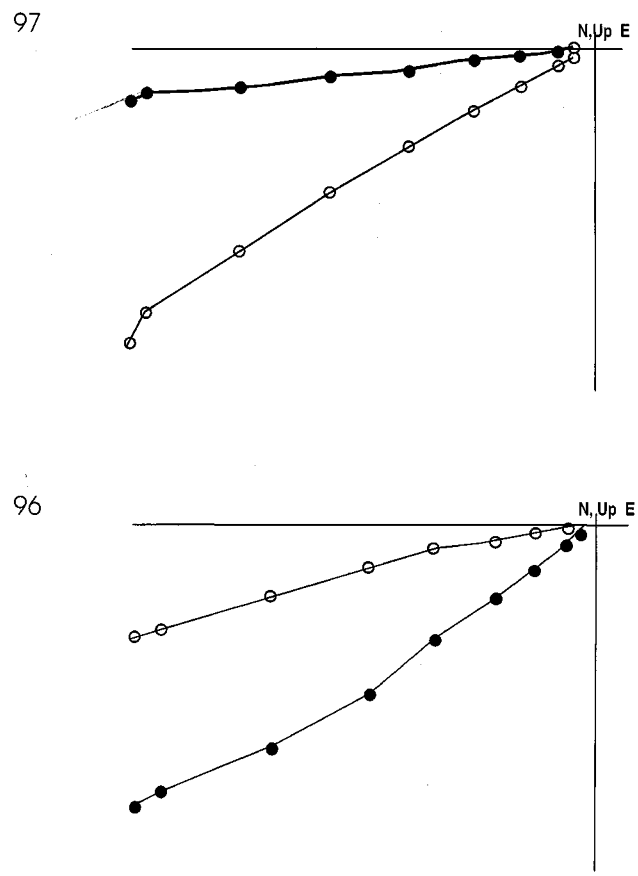


Fig. 4. Examples of orthogonal vector plots for samples 96 and 97. Vector plots are obtained by progressive alternating field (AF) demagnetization. Open symbols correspond to vertical component and solid symbols correspond to horizontal component. Different vectorial compositions from univectorial magnetizations to multivectorial magnetizations with overlapping coercivity spectra can be observed.

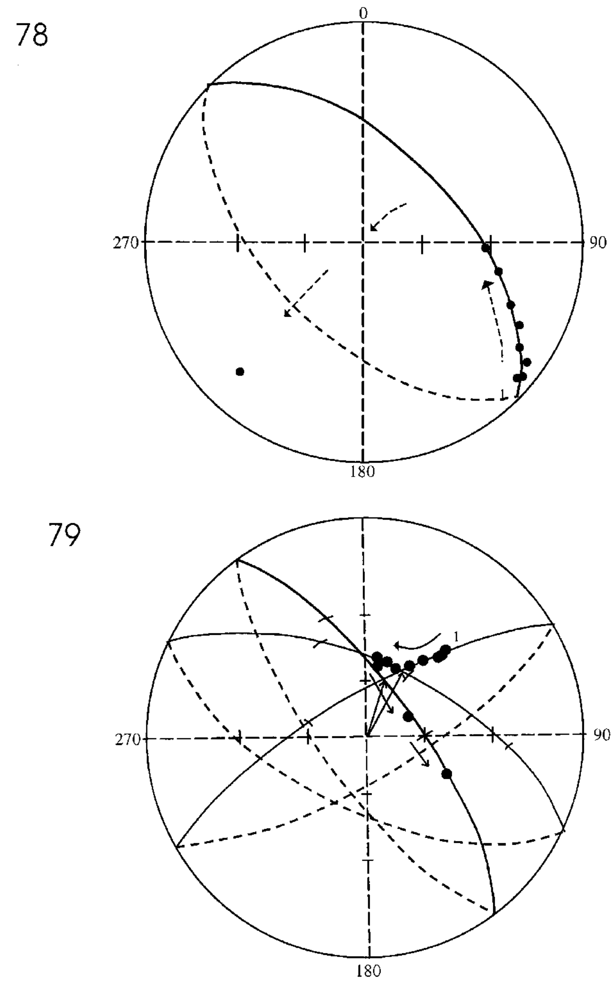


Fig. 5. Examples of remagnetization circles for samples from site M-02. Data for sample 78 and sample 79 (below) are included to illustrate the data. Plots are in equal-area stereograms.

volcanoes shows a 100 km offset about 101° W, which Connor (1990) relates to the subducted plate segmentation model of Carr *et al.* (1974).

Tectonic and paleomagnetic studies have documented the occurrence of vertical axis rotations of crustal blocks in orogenic systems (Kissel and Laj, 1988). Deformation patterns are usually complex with normal, thrust and strike-slip faults giving rise to distinct structural domains of varying shapes and orientations. Rotations of crustal blocks bounded by strike-slip faults usually characterize wide deformation zones in the continental interiors and margins (e.g., McKenzie and Jackson, 1986; Ron *et al.*, 1984; Scotti *et al.*, 1991; Mattei *et al.*, 1995). Within the TMVB, block rotations have also been documented, e.g., in the Acambay graben (Soler-Arechalde and Urrutia-Fucugauchi, 1994, 1997, 1999) and in the eastern Chapala graben (Urrutia-Fucugauchi and Rosas-Elguera, 1994). The remanent magnetization directions for volcanic units in the Valle de Santiago area are rotated counterclockwise with respect to the Plio-Quaternary expected directions, which suggests the occurrence of block rotations. The overall mean paleomagnetic direction based on 10 volcanic units is Dec= 353.7° and Inc=39.2°, with k=42 and α_{95}=7.6°. The corresponding mean pole is PLAT=78.4° N and PLONG = 180.0° E, to the left of the reference poles estimated for cratonic North America and northern Mexico (Urrutia-Fucugauchi, 1984). The angular difference quantified in terms of the rotation R parameter is about –6.3°+6.1° degrees, which suggests that the area rotated CCW (the R values corresponding to the Pliocene and Quaternary are summarized in Table 3). The negative R value is within the statistical uncertainty and further study is required to evaluate a possible tectonic implication.

The three volcanic units that show intermediate directions (site S05, M-04 and M-05), with easterly or westerly declinations, do not appear to be related to independent smaller blocks. The angular between-site dispersion possi-

Table 2

Summary of paleomagnetic data for the Valle de Santiago volcanic field.

Site	N/Ns	Dec/Inc	α_{95}	k	Observations
S-01	7/10	357.6/35.7	6.1	121	Andesite
S-01b	5/7	2.0/42.5	5.6	110	Andesite
S-02	8/10	20.4/32.7	6.6	62	Maar Alberca
S-03	7/4	359.7/41.1	6.5	38	SE Cerro Prieto, N Moroléon
S-04	8/10	348.0/40.5	12.3	21	N.C. Jara Brava, E Moroleón
S-05	6/6	124.0/65.6	6.0	100	S C. El Capulín
S-08	9/12	344.0/32.2	3.2	158	W Yuriria, Salamanca-Uriangato
S-09	6/10	353.9/43.9	11.0	125	SW Casacuerán, basalto
M-01	8/11	166.0/-46.0	3.2	298	N. Salamanca
M-02	6/9	344.7/30.0	10.4	55	La Compañía, 3 km. Valle de Santiago
M-03	6/6	338.7/51.0	10.3	26	Jaral del Progreso, 14 km Valle de Santiago
M-04	6/7	319.6/27.3	9.2	4	Hoya Rincón Parangueo , NW Valle de Santiago
M-05	6/6	306.5/44.7	14.8	10	Maar San Nicolás (1.18± 0.17 Ma)
Mean	11	340.3/38.6	8.6	29	(pole position: 75.3ºN, 177.0º E)
Mean	10	353.7/39.2	7.6	42	(pole position: 78.4ºN, 180.0º E)

Notes: N/Ns, number of samples /number of samples collected; Dec/Inc, site mean declination/inclination of characteristic remanence; α_{95} , 95% cone of confidence; k, concentration parameter.

bly reflects factors other than differential tectonic rotations. Sites M-04 and M-05 in the Rincón de Parangueo and San Nicolás maars present small concentration parameters, with k values of 4 and 10, respectively. This may suggest effects of incompletely separated characteristic NRM directions, remagnetization effects, local structural complications, etc. In contrast, site S-05 in Cerro Capulín presents high k values and good directional grouping. The possible structural implications require further study. The volcanic units studied are distributed to the east and west of the Valle de Santiago maar lineament, suggesting that the structural blocks (e.g., Figure 8) formed at the intersection zone between the fault system of Chapala-Tula and the NNW-SSE maar lineament are rotated in a similar sense and amount. There are other areas where similar rotation patterns, with coherent sense of rotation, have been documented. For instance, in the area between the San Andreas and the San Jacinto faults in California, a series of left-lateral faults delimit a series of crustal blocks that rotate CW in response to right-lateral shear along the San Andreas and San Jacinto master faults (Nicholson *et al.*, 1986).

The relationships between tectonism and volcanic activity in the TMVB have been much discussed. The oblique orientation of the volcanic arc in relation to the trench (about 15°) has led researchers to propose additional controls on magmatic activity, besides the Rivera and Cocos plate subduction. These factors may include bending and/or faulting of the subducted plate, influence of the crustal structure of the overriding plate, effect of pre-Neogene crustal weakness zones, and Neogene tectonism (e.g., Molnar and Sykes, 1969; Mooser, 1972; Urrutia-Fucugauchi and Del Castillo, 1977; Pasquare *et al*., 1988; Johnson and Harrison, 1990). Pasquarè *et al.* (1988) have examined the stress field evolution in the central sector of the TMVB. They proposed that an ENE-WSW extensional phase related to Basin and Range deformation occurred during the middle Miocene to the early Pliocene. NE-SW compression including reverse, dextral and sinistral strike-slip faulting followed this tectonic phase. Sinistral transtension with NW-SE least principal stress and sinistral normal-slip faulting became dominant during the early Pleistocene. During the late Pleistocene-Holocene, transtension became concentrated along the regional E-W faults. Johnson and Harrison (1990) described the Chapala-Tula fault zone in terms of a structural trend continuing eastward from the Chapala rift with a series of aligned fault scarps (Figure 9). Most of the fault scarps are oriented E-W or NE-SW with the down block to the north. Faults in the area S and SE of Lake Chapala cut Plio-Pleistocene cones. In its eastern segment, the system includes seismically active faults, like the Acambay, Venta de Bravo and Pastores faults (Astiz, 1986; Suter *et al*., 1992). Faults in the central Acambay graben show evidence of displaced surficial sediments, suggesting recent activity associated with earthquakes (Ramírez-Herrera *et al.*, 1994). Geomorphological studies in the Acambay graben document neotectonic activity, with fault

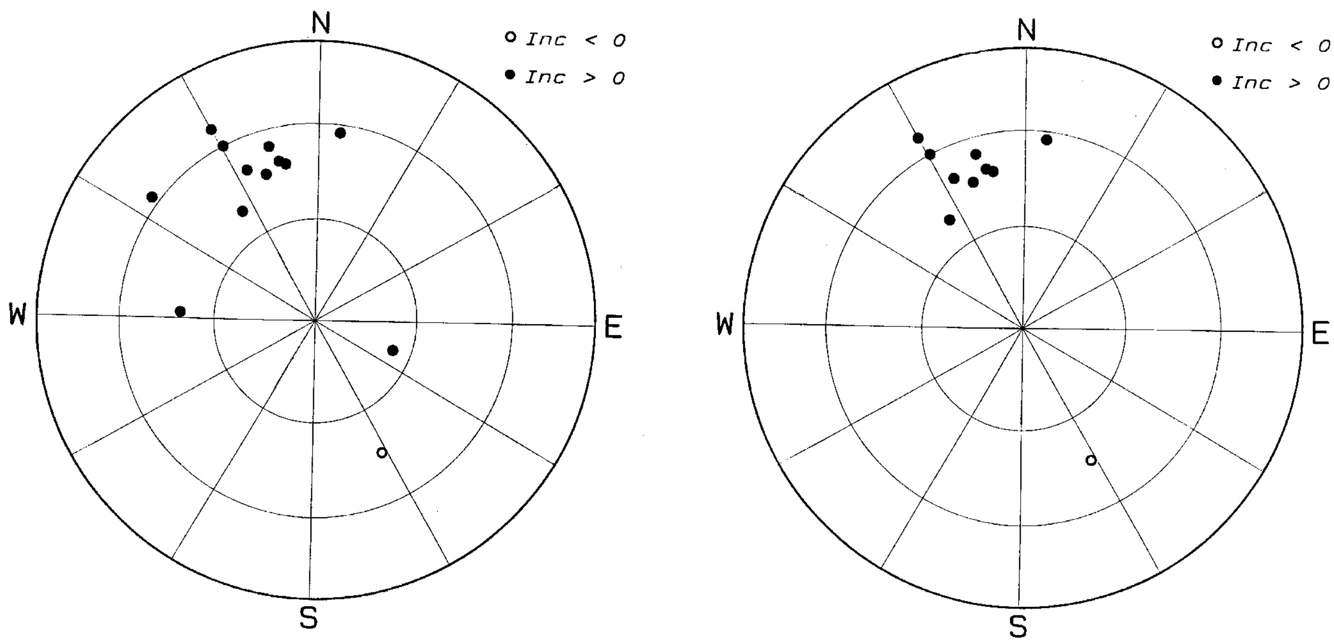


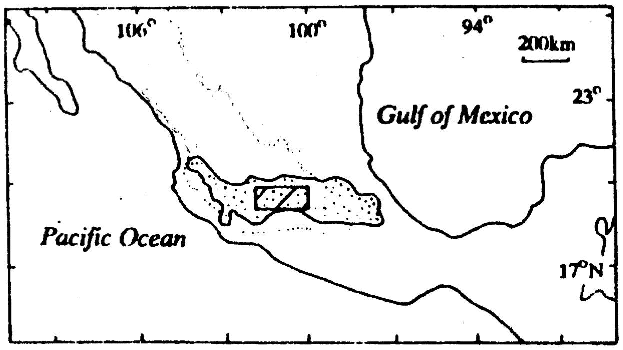
Fig. 6. (a) Summary of site mean directions for all sites studied, and (b) summary of site mean directions for sites selected to calculate the overall mean (see Table 2 and text).

Table 3

Summary of paleomagnetic data for the Trans-Mexican Volcanic Belt

Locality	N	Lat (ºN)	Long (ºE)	A_{95}	R±ΔR	F±ΔF	Age
1. E.Mexico volcanics		80.1	184.1	8.1	-8±11	-4±8	M-Q
2. Basin Mexico	42	87.5	164.5	3.0	-2±4	-3±6	Q(B)
3. Basin Mexico	19	88.1	302.8	6.5	5±7	-4±6	eM-P
4. Basin Mexico	22	88.4	79.3	7.2	8±8	6±8	eO-M
5. Basin Mexico	27	80.7	154.3	5.3	-9±6	4±5	P-Q
6.Jantetelco-Tepexco	9	33.7	176.3	10.0	-56±13	6±13	M
7. NE Jalisco	7	68.1	181.1	(10.0)	-20±14	1±12	O-M
8. Guerrero volcanics	6	54.8	164.5	(8.6)	-32±11	11±12	O-M
9. Balsas Fm.	14	54.1	183.4	(12.0)	-40±14	18±14	Pa-E
10.Acambay volcanics							
Group A	9	80.6	11.3	4.6	9.9 ± 6	7.5 ± 5	P-Q
Group B	13	78.4	172.5	4.3	-12.4 ± 5	0.2 ± 4	P-Q
11. R. Santiago	3	81.2	128.1		-6	6	P
12. R. Santiago	4	79.1	180.6		11	-6	M
13. Amatlan volcanics	8	81.9	197.2	(9.1)	-8		Q
14. E. Chapala L.	16	74.0	159.7	7.6	-17±7	3±6	M-Q
15. Volc. Mexico W	16	84.9	155.9	8.9	5	3	P-Q
16. Valle de Santiago	10	78.4	180.0	7.6	-6±6	-6±6	M-Q

Number of sites, N; Latitude, Lat; Longitude, Long; 95% cone of confidence, α_{95}; Rotation parameter and statistical uncertainty R±ΔR; Flattening parameter and statistical uncertainty F±ΔF; Age: Q, Quaternary; Q(B), Quaternary (Brunhes chron); P, Pliocene; M, Miocene; eM, early Miocene; O, Oligocene; eO, early Oligocene; E, Eocene; Pa, Paleocene. Entries 1 to 15 are taken from data compilations by Urrutia-Fucugauchi and Rosas-Elguera (1994) and Soler-Arechalde and Urrutia-Fucugauchi (in press). It includes new data (entries 1 and 5) not yet published by Osete *et al*. (in press) and Ruiz-Martínez *et al*. (in press). Entry 16 is from this paper.



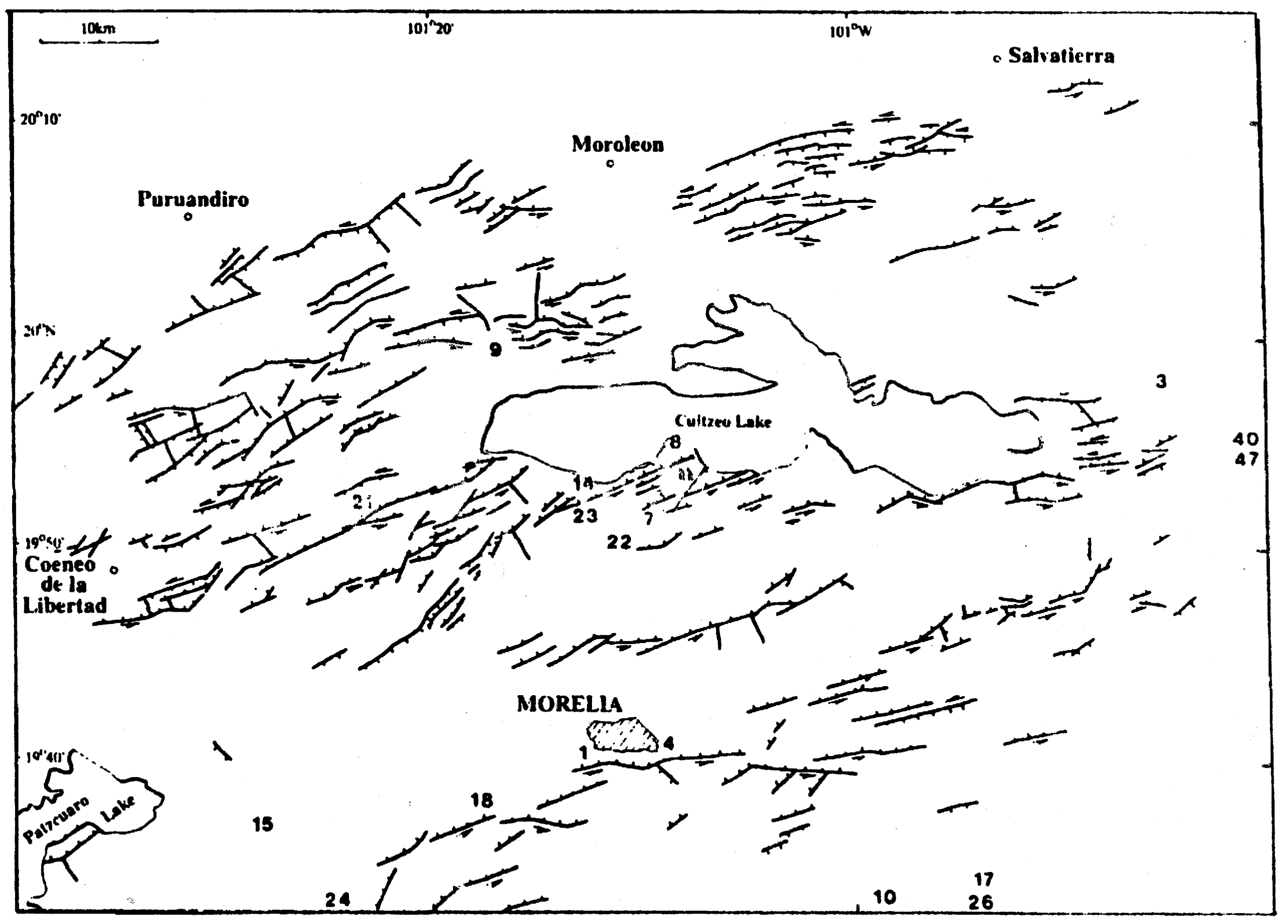


Fig. 7. Structural map for the area of northern Michoacán (taken from Tibaldi, 1989). Observe the regional NE-SW trend of the major Pleistocenic faults. The Cuitzeo Lake is oriented E-W, and parts of its margin is controlled by faults (particularly its southern margin). The NW-SE trend of the elongated maar field of Valle de Santiago is oriented normal to the regional faulting trend. The arrows indicate the strike-slip movement inferred for some of the major faults, which is dominantly left lateral.

scarps and triangular facets showing normal faulting and sag ponds, pull-apart basins and offset drainage showing left-lateral strike-slip faulting (Ramírez-Herrera *et al.*, 1994).

Central and southern Mexico is subject to regional sinistral shear driven by oblique plate subduction along the trench, which may result in fragmentation of large crustal blocks (Figure 9). Johnson and Harrison (1990) have identified three large blocks: the Jalisco, Michoacán (-Oaxaca?) and Guerrero blocks (Figure 9). Left-lateral motion along the Chapala-Tula and Chapala-Oaxaca fault zones results in southeastward displacement of the southern Mexico conti-

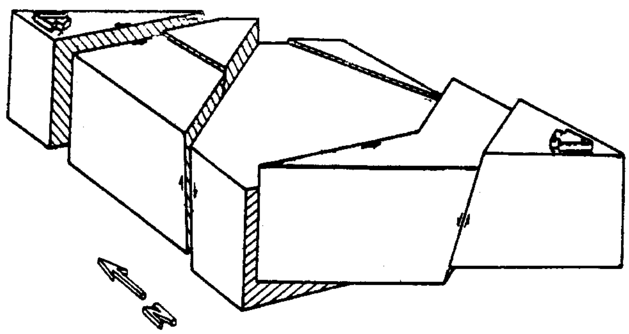


Fig. 8. Schematic representation of block movement inferred for northern Michoacán (taken from Tibaldi, 1989).

nental margin. Block rotations have been documented at the western and eastern ends of the Chapala-Tula fault zone in the eastern Chapala graben and the Acambay graben (Table 3).

This study documents block rotations in the Valle de Santiago volcanic field. This area lies at the intersection of an E-W fault system and an older NNW-SSE system related to southern Basin and Range deformation. The block rotations may help to accommodate the tectonic deformation as in other regions (e.g., Ron *et al*., 1984; McKenzie and Jackson, 1986; Kissel and Laj, 1988; Scotti *et al*., 1991). Active volcanic activity in the MGVF, represented by the Paricutín, Jorullo and Tancitaro volcanoes (Figure 9), is concentrated at the southern sector of the field along the Chapala-Oaxaca fault zone. It is interesting to note that several stratovolcanoes and cinder cone fields are located at the intersection of the fault systems, e.g., the Nevado de Toluca, Popocatépetl, and Jorullo volcanoes, and the Valle de Santiago maar field (Figure 9).

Rotation of tectonic domains implies horizontal decoupling at some depth, separating usually upper crustal tectonic domains of various sizes affected by distributed shear deformation. The depths of horizontal decoupling are related

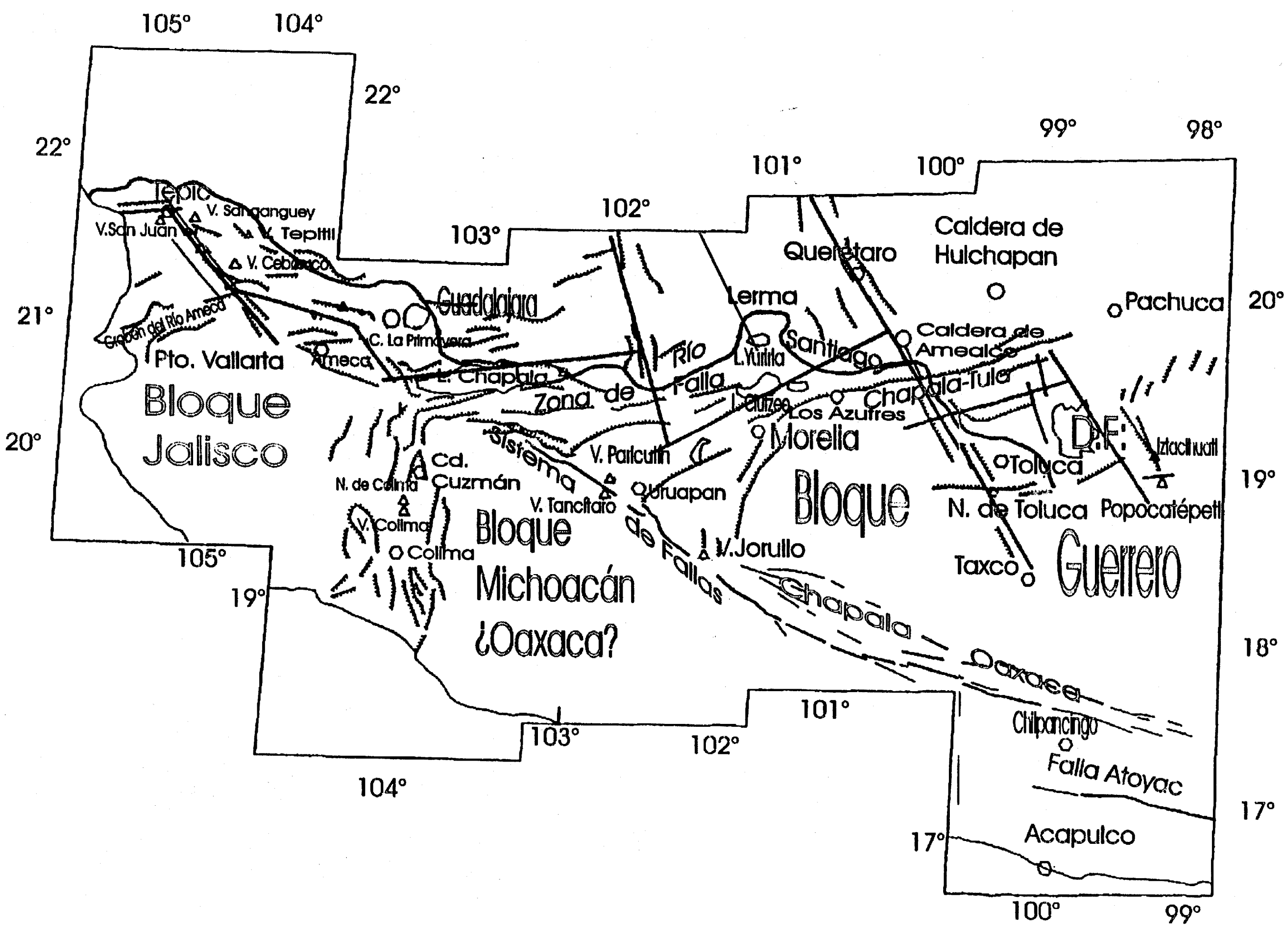


Fig. 9. Schematic tectonic map for central and western Mexico (taken from Johnson and Harrison, 1990; Soler-Arechalde and Urrutia-Fucugauchi, 1994) showing the regional trends of the Chapala-Tula zone. The trend of the Lerma River is controlled by the major structural pattern in the region. Observe the changes in the basin corresponding to the intersections of the ENE-WSW Chapala-Tula system with the NW-SE trend of the Valle de Santiago elongated maar field. A similar pattern is shown at other major intersections of the fault systems, particularly at the Querétaro-Taxco system.

to the behavior of the near-vertical faults. Unfortunately, relatively little information is available for the middle and lower crust in strike-slip faulting environments (e.g., Lemiszki and Brown, 1988). If the maar lineament is related to a deep crustal discontinuity that enables the magmas to reach the surface, then the lineament represents a major master fault and tectonic domain boundary. Lower crustal xenoliths in some of the maars (Uribe-Cifuentes and Urrutia-Fucugauchi, 1992) provide additional support for deep-seated conduits and rapid rise of magma. Crustal thickness in the area is around < 45 km (Molina-Garza and Urrutia-Fucugauchi, 1993). Crustal thickness increases from the margins towards the continental interior (Mexican Altiplano) and the eastern TMVB. In the central sector, the crust is thicker (up to 47 km) beneath the Pátzcuaro area in the central MGVF. The E-W regional pattern of Bouguer gravity anomalies in the TMVB correlates with the general trend of the volcanic activity in the central and western sectors. A large NNW-SSE anomaly is associated with the Querétaro-Taxco fault system, which has been related to a major crustal discontinuity (Molina-Garza and Urrutia-Fucugauchi, 1993). Large anomalies are also associated with the Pátzcuaro and Cuitzeo lakes, emphasizing the structural control for these basins. Information concerning the deep crustal structure beneath the TMVB does not yet permit a detailed correlation with the distribution and type of volcanic activity.

Additional paleomagnetic studies are required to identify the rotation mechanisms and the relationships to the structural elements. Several models have been proposed to account for rotations in different tectonic settings (e.g., Ron *et al*., 1984; McKenzie and Jackson, 1986; Kissel and Laj, 1988; Scotti *et al*., 1991). Further stratigraphic studies and radiometric dating are required to analyze the temporal evolution of deformation and its possible relations with the spatial-temporal changes in the regional stress field (e.g., Pasquare *et al.*, 1988; Suter *et al*., 1992).

Studies of the volcanic stratigraphy of the region provide some radiometric dates that assist in constraining the evolution of igneous activity in the MGVF (e.g., Silva-Mora, 1979; Murphy, 1982; Ban *et al*., 1991; Uribe-Cifuentes, 1992; Delgado-Granados *et al*., 1995). The magnetic polarity of most units is normal, except for one unit (site M-01) from the Cerro Guantecillos, north of Salamanca. Following the stratigraphic division proposed by Murphy (1982), there was a period of andesitic and basaltic-andesitic volcanic activity prior to the maar formation, bracketed with a K-Ar date of 6.88 Ma on Cerro Guantes. The oldest K-Ar date on units associated with the maars is 1.2 Ma for the maar San Nicolás. The other maars present younger dates, from 0.38 Ma in La Cintura to 0.073 in maar La Alberca (Table 1). Reference to the geomagnetic polarity time scale for the Neogene (Baksi, 1993) suggests that the activity in the area could have recorded both normal and reverse polarity. The dominant normal polarity in the volcanics of Valle de Santiago suggests a young age within the Brunhes Chron. This dominant normal polarity contrasts with magnetostratigraphic results from nearby areas as in the Acambay graben or the Sierra de las Cruces in the Valley of Mexico, where normal and reverse polarities have been recorded (Mora-Alvarez *et al*., 1993; Soler-Arechalde and Urrutia-Fucugauchi, 1994; Osete *et al*., 1999). The volcanic activity in the Valle de Santiago area occurred within the Brunhes Chron, and likely some older chrons according to the available K-Ar dates (Table 1).

ACKNOWLEDGMENTS

We acknowledge the assistance provided by A. M. Soler, C. Caballero, M.L. Osete and R. Fernández. We thank M. Espinoza for assistance in the laboratory. Useful comments by two reviewers have been helpful in improving the paper. Economic support has been provided by the Instituto de Geofísica, UNAM and European Community grant CI1-CT94-0114. R. M. Uribe acknowledges the support provided by a CONACyT scholarship.

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