Geofísica Internacional (1994), Vol. 33, Num. 4, pp. 565-574

Regional rigid-block rotation, small domain rotations and distributed deformation within the Acambay graben, central Trans-Mexican Volcanic Belt: paleomagnetic implications

Ana María Soler Arechalde and Jaime Urrutia Fucugauchi
Laboratorio de Paleomagnetismo y Geofísica Nuclear,
Instituto de Geofísica, UNAM, MEXICO

Received: February 9, 1993; accepted: August 26, 1994.

RESUMEN

Declinaciones paleomagnéticas para unidades volcánicas dentro del graben de Acambay presentan rotaciones contrarias a las manecillas del reloj con respecto a las direcciones de referencia. La dirección promedio del área comprende desde -18.5 ± 7.5 a -15.8 ± 7.2 grados, asumiendo que la región se comporta como un dominio tectónico coherente y rígido. La deformación a nivel local parece más compleja y varios dominios tectónicos pueden ser identificados. Estimaciones de rotaciones locales han alcanzado hasta -49 grados y dentro del graben alrededor de -40 grados. Las diferencias angulares podrían ser resultado de: a) variación secular, b) rotaciones diferenciales de dominios tectónicos pequeños, c) deformación interna dentro del dominio rotado, d) diferencias en edades y tiempos de rotación, e) efectos de muestreo y medición f) complejidades estructurales de orden local que pudiesen dar origen a correcciones erróneas, g) una combinación de los anteriores factores. Los resultados paleomagnéticos son analizados de acuerdo con la distribución geográfica dentro del graben, posición relativa de los sitios de muestreo con respecto a los escarpes de falla, etc. Los factores (a), (b), (c) y (d) son considerados importantes. Los resultados apoyan la ocurrencia de una rotación en contra de las manecillas del reloj de un gran dominio, posiblemente relacionado a esfuerzos regionales dextrales y transtensión dentro del arco magmático. Localmente las deformaciones dentro del graben parecen distribuidas en dominios menores, los cuales presentan montos diferentes de rotaciones antihorarias.

PALABRAS CLAVE: Paleomagnetismo, neotectónica, rocas volcánicas, Cinturón Volcánico Mexicano, graben de Acambay, México central.

ABSTRACT

Paleomagnetic declinations for volcanic units within the Acambay graben, are rotated counterclockwise by various amounts with respect to expected reference directions. The average overall mean rotation is from -18.5 ± 7.5 to -15.8 ± 7.2 degrees, assuming the region behaves as a coherent rigid tectonic domain. Deformation on a local scale seems more complex and several tectonic domains can be identified. Site-mean rotation estimates are as high as -49 degrees, with rotations within the graben around -40 degrees. The angular differences among the site-mean paleomagnetic directions mainly result from: (a) paleosecular variation, (b) differential rotation of small tectonic domains, (c) internal deformation within the rotated domain, (d) age differences and timing of rotation, (e) sampling and measurement effects, (f) local structural complexities, apparent rotations due to improper structural correction, and (g) a combination of these factors. The paleomagnetic results are analyzed for geographic distribution within the graben, relative position of sampling sites with respect to fault scarps, etc. Factors (a), (b), (c) and (d) are considered important. Results support the occurrence of a counterclockwise rotation of a large domain, possibly related to regional sinistral shear and transtension within the magmatic arc. Locally, deformations within the graben seem distributed among various small domains, which show different amounts of counterclockwise rotation.

KEY WORDS: Paleomagnetism, neotectonics, volcanic rocks, Trans-Mexican Volcanic Belt, Acambay graben, central Mexico.

1. INTRODUCTION

The Trans-Mexican Volcanic Belt (TMVB) is a large elongated volcanic province which roughly trends east-west across central Mexico. The TMVB is currently associated with subduction of the Cocos plate at the Middle American trench (MAT) beneath southern Mexico; its trend is oblique to the trend of the MAT, and the trench-arc gap (distance between trench axis and volcanic front) increases from west to east along the belt. The characteristics of the TMVB vary across and along this continental arc. At least four major sectors can be identified: (i) The easternmost sector, along the Gulf of Mexico coastal plain, includes Los Tuxtlas volcanic field which is characterized by dominant alkaline volcanics. This sector has been considered as a distinct volcanic province (with a NW-SE trend). (ii) The east-central sector extends roughly between the Perote-Pico de Orizaba range to the Basin of Mexico and is characterized by elevated topography and high active stratovolcanoes. (iii) The west-central sector extends to the east of the Toluca-Lerma valley to the region of the Chapala lake (Figure 1). This sector is characterized by the widespread cinder cones and shield volcanoes of the Michoacán-Guanajuato field. The topography is lower and major E-W structural lineaments and faults are prominent. (iv) The western sector extends from the Chapala lake region to the Pacific coast (Figure 1). Volcanic activity is found along two elongated belts: a N-S belt along the Colima graben, which includes the Cantaro-Nevado-Colima range, and a NW-SE belt along the Tepic-Chapala graben, characterized by several stratovolcanoes such as Ceboruco and San Juan.

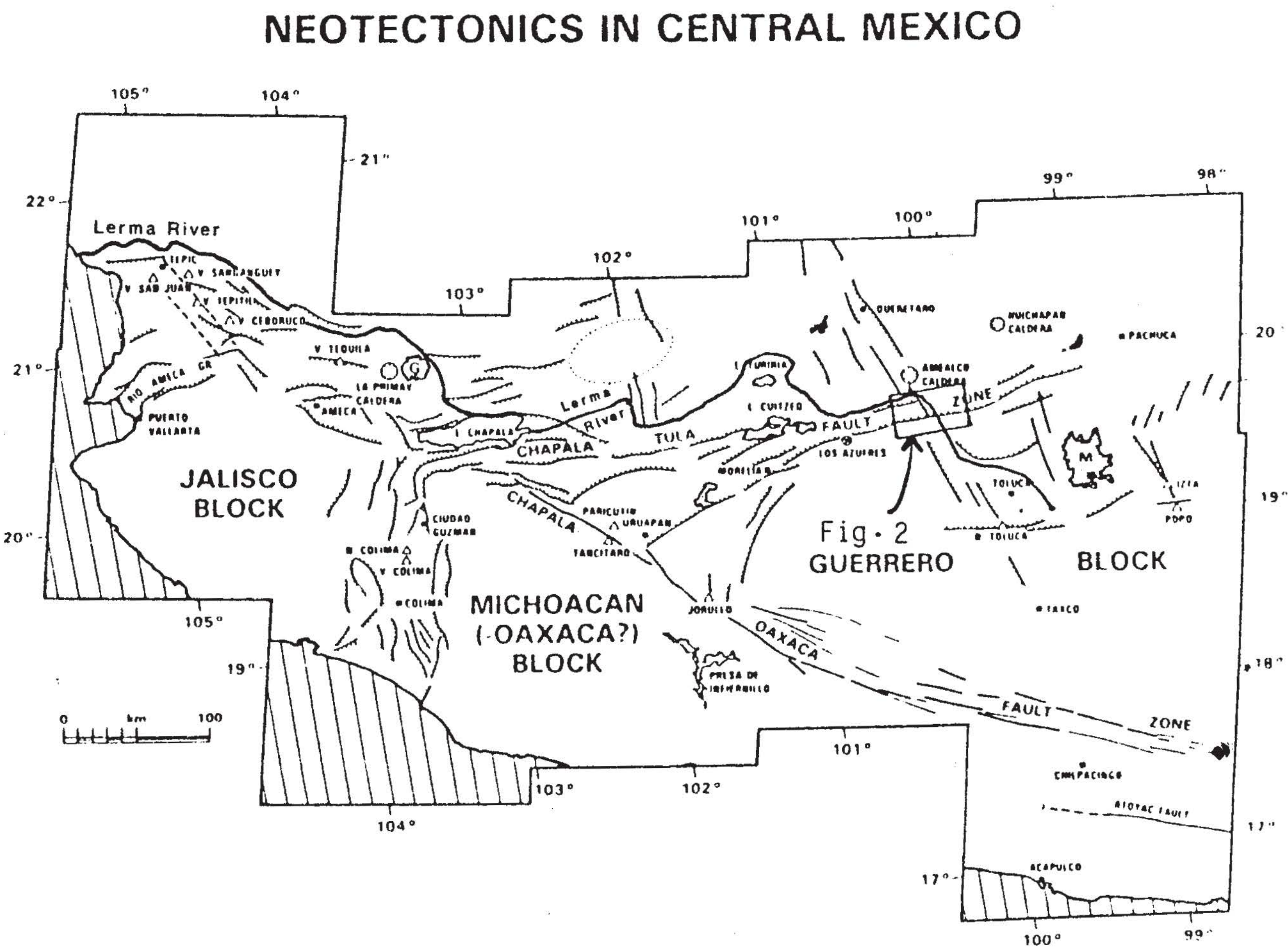

Fig. 1. Tectonic sketch of western and west-central Mexico (modified slightly from Johnson and Harrison, 1990). The Acambay graben (small rectangle) is located at the eastern end of the Chapala-Tula fault zone, at its intersection with the NNW-SSE Querétaro-Taxco fault zone. Relative motion among southern and central Mexico with respect to the North America plate may be distributed among major fault systems, including the Chapala-Tula and Chapala-Oaxaca faults.

In this paper preliminary results for the Acambay graben region (Figure 2) are reported. The Acambay graben is located at the northwestern end of the east-central sector of the TMVB (small rectangle, Figure 1) and is marked by seismically active large fault scarps (Suter *et al.*, 1992). Two large shallow earthquakes occurred in the region in this century: the November 19, 1912 Acambay Ms = 7.0 earthquake and the February 22, 1979 mb = 5.3 Maravatio earthquake (Urbina and Camacho, 1913; Astiz, 1980; Suter *et al.*, 1992). The region studied in this project extends approximately from west of Maravatio to Acambay - Atlacomulco (Figure 2). Paleomagnetic results for the Acambay graben region suggest a 15.8 ± 7.2 counterclockwise rotation which has been related to regional left-lateral shear (Soler-Arechalde, 1990; Soler-Arechalde and Urrutia-Fucugauchi, submitted, 1994). In this paper the relationships between the paleomagnetic results and the structural features within the graben and their implications for the neotectonic activity in the west-central sector of the TMVB are discussed.

2. ACAMBAY GRABEN

The Acambay graben features many dominantly east-west faults which deform a volcanic terrain that includes extensive ignimbritic units, cinder cones, lava flows and the large Amealco caldera. The structure is well defined in Landsat Thematic Mapper (TM) images (Johnson and Harrison, 1990), aerial photographs and topographic maps, and has been studied in detail by Suter *et al.* (1992). The main graben structure is defined by steep fault scarps. The southern boundary is formed by the Venta de Bravo and Pastores faults, which present long escarpments with up to 300 m of relief. The northern boundary is the Acambay-Tixmadeje fault system which presents fault scarps of up to 400-500 m. The northern boundary is marked by a gravity Bouguer anomaly, with a 30 mgal difference between the graben and the block to the north. The transition zone between the Venta de Bravo and Perales faults is at the intersection with the NNW-SSE Amealco-Perales fault zone (Figure 2) and is characterized by an en echelon fault

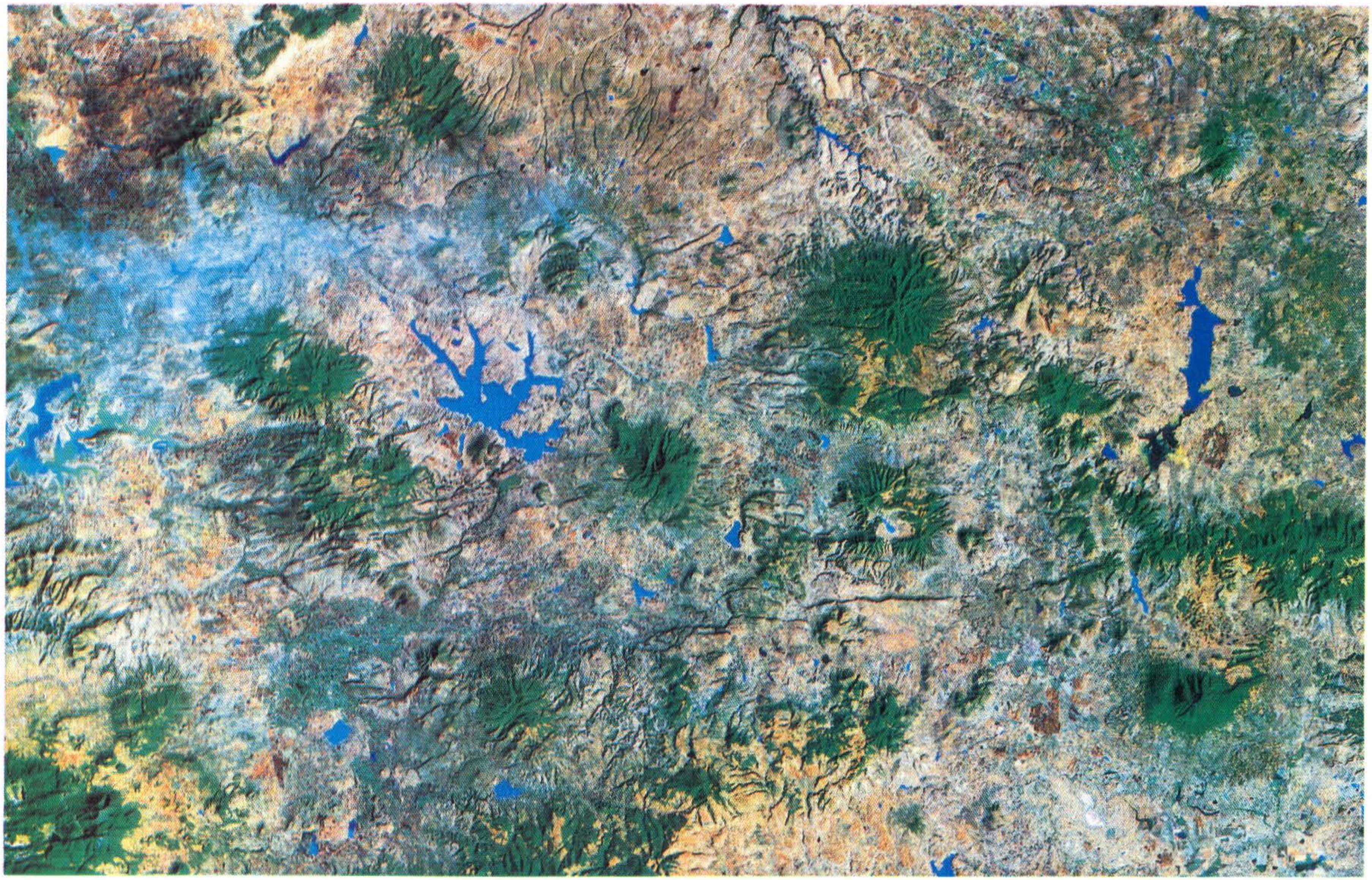

Fig. 2. Landsat Thematic Mapper image of the Acambay graben. Major fault scarps and some structures can be observed in the image. Note small pull-apart basins within the Venta de Bravo fault, just south of Venta de Bravo town. TM image taken on August 19, 1986 by NASA Landsat system.

pattern and small extensional jogs and pull-apart basins (Figure 2).

The landsat TM image for the graben (Figure 2) corresponds to a combination of spectral bands 2 (0.52-0.60μm), 4 (0.76-0.90 μm) and 7 (2.08-2.35 μm). Band 2 comprises the visible green reflectance peak of vegetation. Band 4 is particularly useful for delineating water bodies and biomass content. Band 7 is the 'geological band' that allows discrimination of different lithologies, particularly clay minerals and mapping of hydrothermal alteration (Johnson, 1987). Fault scarps, structural (e.g., pull-apart basins, drainage patterns) and volcanic features (e.g., cinder cones and Amealco caldera) are presented in detail in this combination of spectral bands. Details of tectonic structures are in Figure 6.

Suter *et al.* (1992) suggest a small left-lateral strike-slip component for the 1979 Maravatio earthquake focal mechanism. They found fault surface striations and pull-apart structures in the Venta de Bravo-Pastores fault system. The pull-apart basin immediately to the south of the Venta de Bravo town is characteristic of a left-lateral strike-slip system (Figure 2). The left-lateral component is also documented in the eastern sector of the graben from the pattern of pressure ridges and tension gashes produced during the 1912 Acambay earthquake.

Volcanic units range from Miocene to Recent (Silva-Mora, 1979; Sánchez-Rubio, 1984). Sánchez-Rubio (1984) reported a K-Ar date of 5 Ma for the Amealco ignimbrite and 13 Ma for the Yondeje andesite. Recent K-Ar ages in the northern sector of the Acambay graben range between about 4.7 and 2.2 Ma (Aguirre-Díaz, 1993).

Our samples are mostly located in the southern sector of the graben. The Amealco ignimbrite has been sampled in a locality north of the graben. Some units of Las Américas Formation (Fries *et al.*, 1977) were sampled south of the graben, in the area of Tlalpujahua and El Oro, and some are east of the intersection of the Acambay graben with the Querétaro-Taxco fault zone (Figure 1). This fault zone, which trends obliquely to the Acambay graben, has a general NNW-SSE orientation and represents an older major tectonic structure. The Querétaro-Taxco fault zone may represent the boundary between the west-central and the east-central sectors of the TMVB.

3. PALEOMAGNETIC RESULTS

Paleomagnetic results for the Acambay graben are summarized in Table 1. Oriented samples from 20 different units distributed within the graben and immediately to the south were collected and analyzed. The natural remanent magnetization (NRM) was measured with a Molspin

Table 1

Summary of palaeomagnetic data for the Acambay graben, central Mexico

Sit	n	Dec	Inc	r	k	α 95	R	ΔR	F	ΔF
n1	8	173.1	-11.5	7.9740	269	3.4	-6.1	5.6	-21.5	6.9
n2*	6	118.1	-9.7	5.9173	60	8.7	-241.1	7.9	23.3	10.6
n3	4	141.9	-29.6	3.9828	174	7.0	-37.4	7.5	-3.5	9.2
n4	6	169.9	-45.8	5.6447	14	11.6	-9.3	13.6	12.8	12.5
n6*	4	6.6	65.2	3.9358	47	13.6	7.4	24.3	-32.3	14.8
n7	6	151.6	-42.0	5.8001	25	13.7	-27.6	14.0	9.6	8.8
n10	5/7	149.0	-42.6	6.7438	23	6.4	-30.2	8.8	9.6	8.8
n11	7	130.4	-37.9	6.8431	38	9.9	-48.8	10.1	4.9	11.6
n15	6	336.3	24.2	5.9369	79	7.6	-23.0	7.7	8.8	9.7
n16	6	341.2	35.8	5.9740	192	4.8	-18.0	6.5	-2.9	7.7
n17	8	166.5	-21.6	7.9529	149	4.6	-12.7	6.1	-11.3	7.5
n18	7/9	172.1	-39.4	6.8553	41	9.5	-7.1	11.1	6.4	11.2
n23	6/8	164.6	-15.3	5.8435	32	12.0	-14.6	11.2	-17.9	13.4
I1	6	147.7	-48.6	5.8688	38	11.0	-31.6	12.8	15.2	12.5
I2	5/6	148.2	-46.3	4.9792	192	5.3	-30.6	8.1	14.4	8.0
I3	6	175.7	-20.2	5.9431	88	7.2	-3.6	7.3	-12.9	9.4
I4	4/5	175.3	-32.1	3.9788	141	7.7	-4.0	9.0	-0.9	9.8
I5*	8	108.0	-71.8	7.9818	384	2.8	-71.3	8.1	38.8	6.6
I6	8	166.5	-39.1	7.9867	528	2.4	-12.7	5.5	5.9	6.5
I7	4/3	7.2	21.0	2.9828	116	11.5	8.0	10.8	12.1	12.9
Mn1	17	161.9	-33.4	16.3144	23	7.5	-15.8	7.2	2.5	7.9
Mn2	20	159.0	-36.4	18.5369	13	9.4	-18.2	8.5	4.9	9.0

Number of samples, n; Declination, Dec; Inclination, Inc; Vector resultant, r; Concentration parameter, k; 95% cone of confidence, α95; Rotation parameter and statistical uncertainly, R±ΔR; Flattening parameter and statistical uncertainly, F±ΔF; Mn2, mean of all samples; Mn1, mean of all samples except N2, N6, I5.

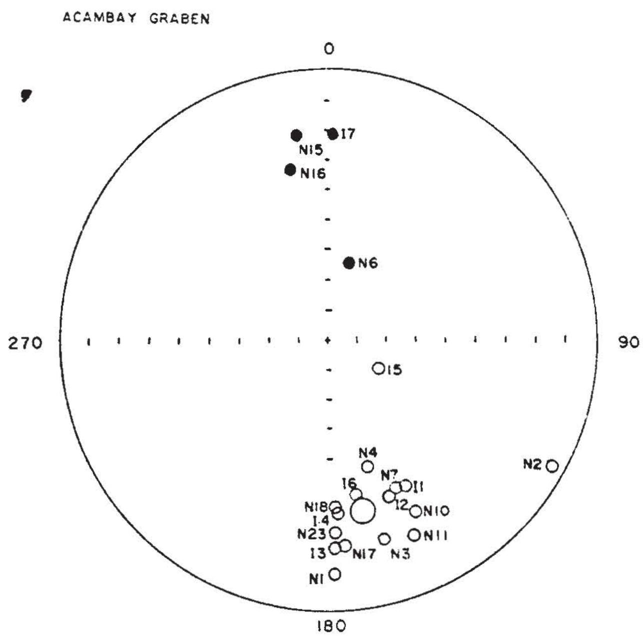

Fig. 3. Site mean directions. See data in Table 1. Open circles, negative inclinations (reverse); full circles, positive inclinations (normal). Reverse polarity directions dominate. Only four sites have normal polarity. The large open circle represents the overall mean direction: N=17, Dec = 161.9, Inc = -33.4, k = 23, α95=7.5; from Soler-Arechalde and Urrutia-Fucugauchi (submitted 1994).

spinner magnetometer attached to an IBM-PC computer. Detailed step-wise alternating field (AF) demagnetization was used to define the characteristic magnetization (chNRM) directions from vector-substraction, end-point and principal component analyses (Dunlop, 1979; Kirschvink, 1980). Site-mean directions and pole positions were calculated for each unit by vector averaging, assuming unit weight to sample directions. Angular dispersion was estimated with standard Fisher statistics (Fisher, 1953). Further details of the experimental study are given in Soler-Arechalde, (1990) and Soler-Arechalde and Urrutia-Fucugauchi (submitted 1994).

Well-defined chNRM directions have been defined for the units studied. Magnetic carriers of the NRM show intermediate and low coercivities and high stability during AF demagnetization. They are dominantly members of the titanomagnetite oxide solid-solution series, with high coercivity minerals, probably hematite from oxidation products. The NRM is a thermoremanent magnetization (TRM). Sixteen units are of reverse polarity and 4 of normal polarity (Table 1). Site-mean directions are summarized in Figure 3.

The site-mean directions are characterized by discordant declinations that are rotated counterclockwise with respect to the expected declinations for the area (based on the Neogene segments of the apparent polar wander paths for northern Mexico (Urrutia-Fucugauchi, 1979, 1984) and for cratonic North America (Irving and Irving, 1982)). To quantify the angular differences, the parameters given by Beck (1980) have been used in terms of the parameter (R) for the declination difference between observed and expected values, and the flattening parameter (F) for the difference between expected and observed inclinations. The associated statistical uncertainties (ΔR and ΔF) are calculated with equations given in Demarest (1983). Positive R values represent clockwise rotation and negative R values represent counterclockwise rotation. Significant F values may indicate latitudinal displacements or tilting.

4. DISCUSSION

The overall mean direction for the Acambay graben is N = 17, Dec = 161.9, Inc = -33.4, k = 23 and α95 = 7.5. The corresponding pole position of Lat = 72 N and Long = 170 E lies to the left of the Neogene northern Mexico or North America APWP segments which suggests a vertical-axis counterclockwise tectonic rotation of the area of about -18.5 ±7.5 to -15.8 ± 7.2 (Soler-Arechalde and Urrutia-Fucugauchi, submitted 1994). In this interpretation, it is assumed that this area behaves as a coherent rigid block with no significant internal deformation. This assumption is supported by the clustering of site-mean directions from the different units within the graben. In the section below, the evidence is examined for internal deformation and differential rotations of smaller domains within this major domain, and the relationships between amount of rotation and structural features within the graben and their implications for the mechanism and kinematics of block rotation are discussed. First, the implications in terms of rigid block rotation (or average rotation of a composite tectonic domain) will be summarized.

The Acambay graben constitutes the eastern end of a major fault system referred to as the Chapala-Tula fault zone (Johnson and Harrison, 1990). The fault zone extends from the Chapala graben in the west to Acambay in the east (Figure 1). Quantification of relative plate motion among the Rivera, Cocos, Pacific and North America plates has proved difficult (e.g., Minster and Jordan, 1979; Bandy, 1992). Present-day plate kinematic models for Mexico and the Pacific area recently suggest a possible sinistral component for a southern Mexico micro-plate, with a motion of some 0-10 mm/year (Johnson and Harrison, 1990; DeMets and Stein, 1990). The difference in relative motion may be accomodated by southeastward and eastward displacements of blocks along the trace of the TMVB (Chapala-Tula fault zone) and trench-parallel zones (Chapala-Oaxaca fault zone) (Johnson and Harrison, 1990; DeMets and Stein, 1990). The Acambay tectonic domain deforms in response to dominant regional E-W left-hand shear and distributed N-S extension occurring within the back-arc region of the TMVB. The preferential orientation of the minimum horizontal stress in the Morelia region, to the east, is NNW-SSE, and in the Acambay graben is NW-SE (Suter, 1991).

The strike-slip component, if distributed over a large area in southern Mexico with relative motion along both the Chapala-Tula and Chapala-Oaxaca fault zones (Johnson and Harrison, 1990; DeMets and Stein, 1990), should result in small displacements along individual fault zones. The magnitude of rotation from the paleomagnetic data is some -18.5 to -15.8 degrees, which may have taken place in the past 5 Ma (i.e., after a major activity of Amealco caldera as indicated by the 4.7 Ma Amealco ignimbritic eruption: Aguirre-Díaz, 1993; Silva-Mora, 1979; Sánchez-Rubio, 1984). This gives an average rotation rate of about 4 degrees per million years, which seems consistent with the maximum sinistral displacements derived from plate kinematic models of less than 10 km/Ma (DeMets and Stein, 1990). However, there are no constraints on the timing of the rotation and these estimates constitute only order-of-magnitude values. Paleomagnetic studies have documented similar regional vertical axis rotations for adjacent areas within the TMVB, particularly in the central-eastern sectors (summary in Urrutia-Fucugauchi and Böhnel, 1988).

The Acambay graben constitutes a structurally complex domain with several faults, pull-apart structures, etc which may define small domains. Local differential rotations of these small domains may produce an apparent scatter of the paleomagnetic rotation parameter values. Internal deformation within the tectonic domain may also contribute to the paleomagnetic angular differences. These aspects are discussed in the next paragraphs.

The angular differences among the site-mean paleomagnetic directions may be related to e.g., (1) paleosecular variation of the geomagnetic field, (2) differential rotation of small tectonic domains, (3) internal deformation, (4) age differences and temporal development of rotation, (5) improper structural corrections, (6) unaccounted local structural complexities, (7) sampling and measurement errors, and (8) a combination of several of these factors.

Factors (5), (6) and (7) are considered unimportant as these units are almost flat-lying, with maximum dips of less than 4 degrees. Apparent tectonic rotations resulting from application of structural corrections and identification of net rotations have been discussed by MacDonald (1980), and the contributions from (7) are partly incorporated in the calculation of statistical uncertainties (ΔR and ΔF). Quantitative evaluation of (1) and (4) is more difficult; both factors could account for the differences observed. Contributions from factors (2) and (3) are discussed below.

The degree of paleomagnetic discordance seems unrelated with distance from the graben boundaries. Figure 4a shows the R results referred to distance of sampling site to the main southern scarp, and Figure 4b shows the corresponding data with respect to the main northern scarp. In both figures, negative distances represent sites located outside the main graben structure. Rotation R values are dominantly negative (indicating counterclockwise rotations) and range up to -49 degrees. The flattening values F are both positive and negative, and are generally less than 15 degrees, indicating no inclination anomaly related to tilting or latitudinal motion. The overall mean value, 3.5 ± 6.5, is well within the statistical uncertainty (Table 1). This suggests that horizontal-axis rotations are less significant than vertical-axis rotations. There is also no apparent relationship between the R values and F values for site-mean results (Figure 5).

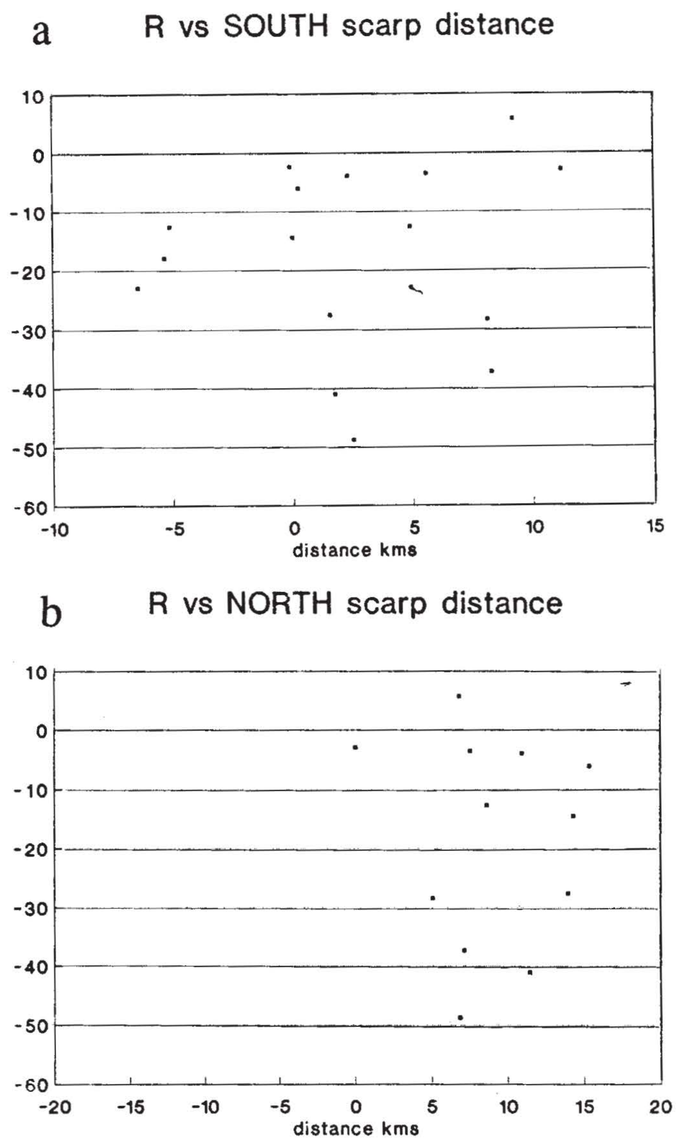

Fig. 4. Plot of R values versus distance to main scarps of Acambay graben. (a) R values plotted as a function of approximate distance to main southern scarp of the Venta de Bravo and Pastores faults. (b) R values plotted as a function of approximate distance to main northern scarp of Acambay-Tixmadeje fault. The negative values correspond to distance away from the main graben.

To investigate the kinematic pattern of block rotation within the tectonic domain and possible geographic distributions of rotated small domains, the paleomagnetic results (mean declinations and statistical uncertainties) for each sampling locality were plotted (Figure 6). Three sites show anomalous inclination values; site N2 shows a shallow inclination and sites N6 and I5 show steep inclinations. They fall outside the grouping of paleomagnetic directions and are not part of the Fisher distribution (Figure 3). N2 and I5 have large R values and N6 has a small value (Table 1). They are not included in the structural analysis.

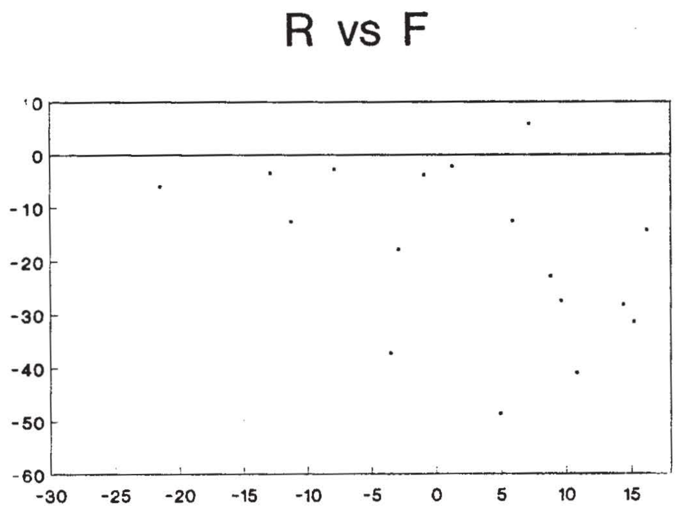

Fig. 5. Plot of R values versus F values for site-mean results in the Acambay graben.

However, inclusion of these three outlier sites would not result change the overall Acambay mean direction significantly (Table 1). There are several apparent patterns in the distribution of the rotation parameter. Six sites feature R values smaller than the statistical uncertainties, indicating no significant rotation (sites N18, N23, I3, I4 and I7). The other 14 sites show rotations of various amounts. The sites located to the south of the graben, in the vicinity of the towns of Tlalpujahua and El Oro (sites N15, N16 and N17) have R values varying from -23 in the west to -13 in the east (Figure 6). The sites between the Venta de Bravo and Pastores faults (sites N1, N4 and N7) have R values from -6 to -27. Site N18 south of the Pastores fault, on the southern block, shows no significant rotation. Similarly, sites I7 and N23 on scarps along the northern faults are not significantly rotated. Sites I3 and I4 east of the intersection with the Querétaro-Taxco zone show no significant R values. However, site I2, in the same zone to the north of site I3, shows a rotation of about -28. This site is within the graben structure south of the town of Acambay. The sites within the graben (N3, N10, N11 and I6) have large R values (i.e., -49 for N11, -41 for N10, -37 for N3 and -13 for I6). Site I6 is at the intersection of one of the E-W fault scarps and the Lerma river canyon.

The paleomagnetic data define several tectonic domains within the deformed region. From south to north and west to east, we have:

(1) Tlalpujahua-El Oro zone on the southern side of the graben features counterclockwise rotations from some -13 to -23. (2) The central-western sector of graben has large R values, around -41 to -49. (3) The deformation zone between the Venta de Bravo and Pastores faults has a range of R values indicating a complex of deformation and occurrence of small tectonic domains. Sites at fault scarps are not rotated. (4) The zone in the graben within the intersection with the NNW-SSE Querétaro - Taxco fault zone has R values from -13 to -37, from S to N. (5) The sector east of the Querétaro-Taxco fault zone shows R values increasing from -4 to -28, S to N, towards the Acambay scarp. (6) The zone to the N of the graben has an R value around -31. Sites located at the fault scarps in the northern boundary of the graben show small R values, within the statistical uncertainties, as for sites along the southern scarp (Figure 6). A simplified picture of some of the apparent tectonic domains across the graben (from S to N) is shown in Figure 7. Note the asymmetric shape of the graben, with larger vertical displacements along the northern scarp; several graben and horst blocks occur. The central cross section (Figure 7a) trends SW-NE along the transition zone between the Venta de Bravo and Pastores faults and the intersection with the Querétaro-Taxco fault zone. It includes domains 1, 3, 4 and 6. The western cross section (Figure 7b) runs S-N to the west of the towns of Venta de Bravo and Buenavista, and includes domains 1, 2 and 6.

Block rotation is an important mechanism of deformation in strike-slip faulting environments (Freund, 1974; McKenzie and Jackson, 1983). Faulted domains in intracontinental regions have special boundary conditions where each domain must remain in contact with its surroundings. The faulted domains are then subjected to internal deformation and block rotation. Paleomagnetic and structural studies have documented the dominant role of rotations in strike slip faulting environments (e.g., McDonald, 1980; McKenzie and Jackson, 1983; Ron *et al.*, 1984). Block rotation can modify the initial angular relationships between the faults and the stress field, with faults often rotating away from the maximum compression directions. Paleomagnetic data provide a simple and powerful tool to investigate the kinematics in deformed domains since these rotations can be accurately quantified.

In extensional tectonic regimes, such as the Basin and Range province, normal faulting has often been considered the dominant deformational mechanism, and strike slip faults are assumed to be secondary features between differentially extended domains of tilted normal faults (e.g., Wernicke *et al.*, 1982). However, block rotation along vertical axes accounts for a large part of the regional horizontal deformation, while tilting in response to the normal faulting is less significant (McKenzie and Jackson, 1983; Ron *et al.*, 1984). The results for the Acambay graben document the importance of block rotation in this intracontinental volcanic arc. The sense of rotation indicates the dominance of left-lateral strike-slip motion in the deformation process. The magnitude of the regional movement is small (less than 10 km/Ma) and therefore the resulting strike-slip offsets are modest. Block rotations along horizontal axes resulting from the normal faulting appears less significant in a regional context. The overall mean flattening parameter is only 3.5 ± 6.5, well within the statistical uncertainty. This suggests no significant tectonic tilt, although local, listric deformation or tilted high-angle faults may account for part of the deformation (Figure 6).

ACKNOWLEDGMENTS

This study is part of a research program in cooperation with Max Suter. Useful discussions and valuable assis–

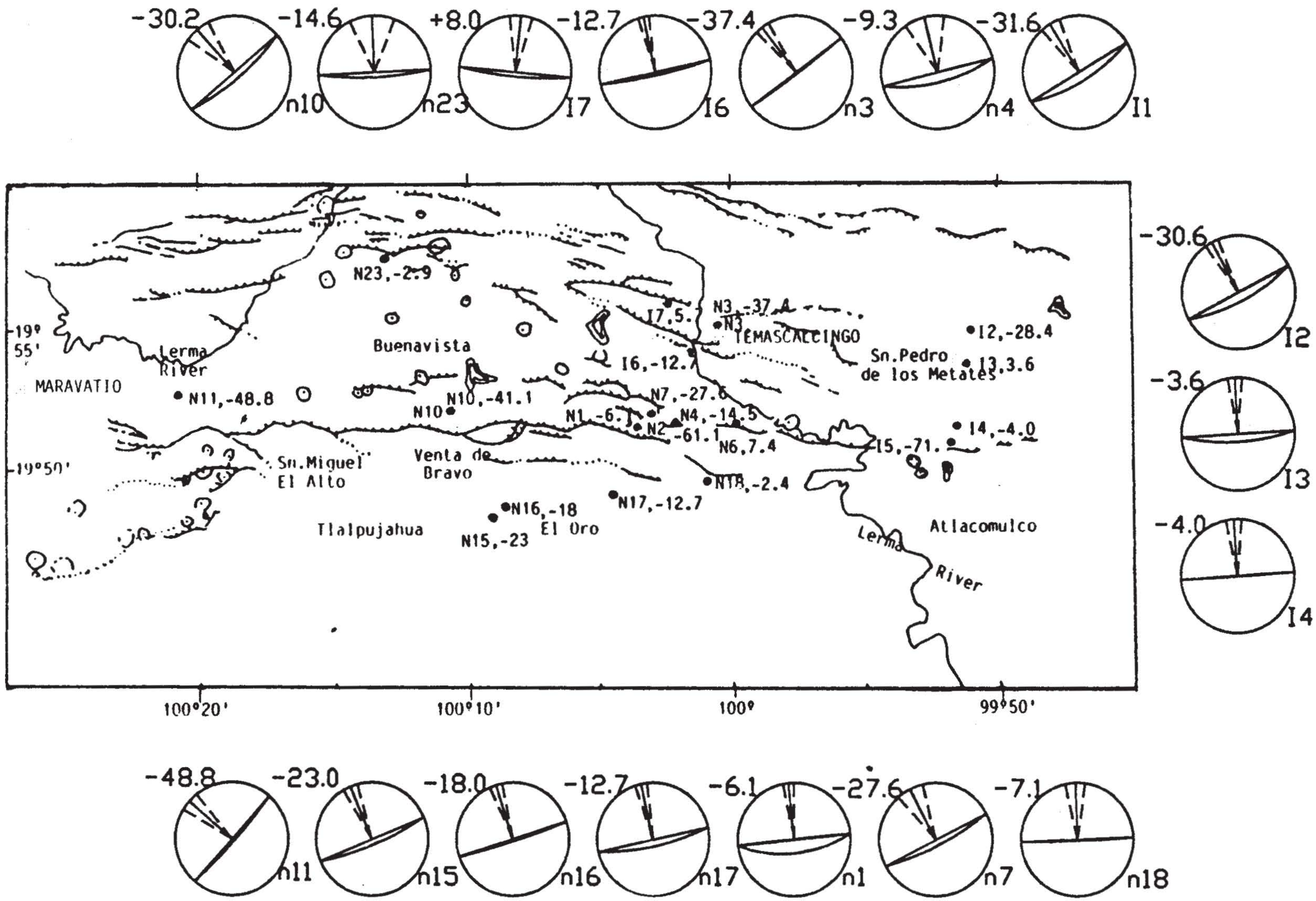

Fig. 6. Site-mean paleomagnetic data for the Acambay graben. Simplified tectonic map modified from Suter *et al.* (1992). Declination values (continuous lines) with associated α95 (dashed lines) are plotted on equal-area stereonets. Most declinations are rotated counterclockwise from north. The estimated rotation angle (R parameter, see text) is indicated at the upper left of each stereonet. Note that magnetizations are of dominant reverse polarity. The northward direction has been plotted for visual orientation proposes (see data in Table 1). The flattening parameter is indicated by the curve normal to the declination line in each stereonet.

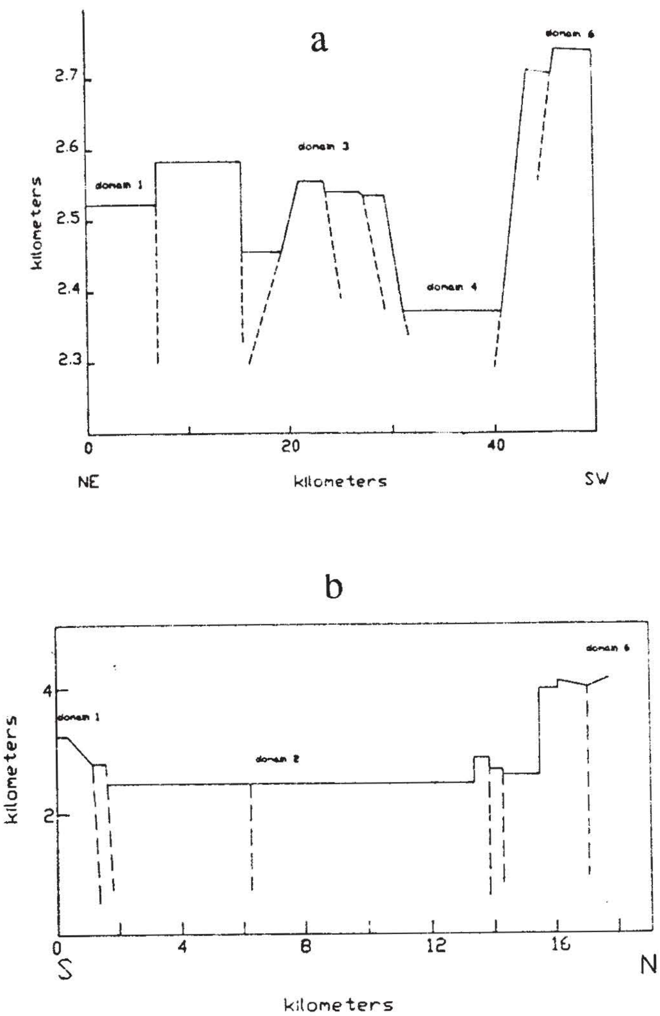

Fig. 7. Simplified structures in the Acambay region, showing idealized tectonic domains and paleomagnetic rotations. (a) central cross section. (b) western section.

tance have been provided by Max Suter, Gerardo Aguirre, Odranoel Quintero, Eduardo Rodal, Jesús Santos, Christopher Johnson, Luis Silva Mora and Gerardo Sánchez Rubio. We thank C. Johnson and H. Lang for the TM image of the graben. A DGAPA scholarship and UACPyP-CCH research grant to A.M. Soler are gratefully acknowledged.

BIBLIOGRAPHY

AGUIRRE-DIAZ, G. J., 1993. The Amealco caldera, Querétaro, Mexico: Geology, geochronology, geochemistry, and comparison with other silicic centers of the Mexican Volcanic Belt. Ph.D. Dissertation, Univ. Texas, Austin, Texas, USA, 401 pp.

ASTIZ, L. M., 1980. Sismicidad en Acambay, Estado de México. El temblor del 22 de febrero de 1979. B. Sc. Thesis, National A. Univ. México.

BANDY, W.L., 1992. Geological and geophysical investigation of the Rivera-Cocos plate boundary: Implications for plate fragmentation. Ph.D. Thesis, Texas A & M University, Texas, USA, 195 pp.

BECK, M., Jr., 1980. Paleomagnetic record of plate margin tectonic processes along the western edge of North America. *J. Geophys. Res., 85,* 7115-7131.

DEMAREST, H. H., Jr., 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data. *J. Geophys. Res., 88,* 4321-4328.

DeMETS, C. and S. STEIN, 1990. Present-day kinematics of the Rivera plate and implications for tectonics in southwestern Mexico. *J. Geophys. Res., 95,* 21, 931-21,948.

DUNLOP, D. J., 1979. On the use of Zijderveld vector diagrams in multicomponent paleomagnetic studies. *Phys. Earth Planet. Inter., 20,* 12-24

FISHER, R. A., 1953. Dispersion on a sphere, Proc. R. Soc. London, Ser. A 217, 295-305.

FREUND, R., 1974. Kinematics of transform and transcurrent faults. *Tectonophysics, 21,* 93-134.

FRIES, C., Jr, C. S. ROSS and A. OBREGON, 1977. Mezcla de vidrios en los derrames cineríticos Las Américas de la región de El Oro-Tlalpujahua, Estados de México y Michoacán, parte centro-meridional de México. *Bol. Inst. Geol. UNAM, 70,* 1-84.

HARLAND, W. B., A. V. COX, P. G. LLEWELLYN, C. A. G., PICKTON, A. G. SMITH and R. WALTERS, 1982. A Geologic Timescale. Cambridge Univ. Press, UK, 131 pp.

IRVING, E., 1964. Paleomagnetism and Its Application to Geological and Geophysical Problems, John Wiley, New York, 399 pp.

IRVING, E. and G. A. IRVING, 1982. Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana. *Geophys. Surv., 5,* 141-188.

JOHNSON, C., 1987. A study of neotectonics in central Mexico from Landsat Thermatic Mapper Imagery. M5c Thesis, Univ. Miami, Florida, USA.

JOHNSON, C. and C.G.A. HARRISON, 1990. Neotectonics in central Mexico. *Phys. Earth Planet. Inter., 64,* 187-210.

KIRSCHVINK, J. L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophys. J. R. astr. Soc., 62,* 699-718.

McDONALD, W. D., 1980. Net tectonic rotation, apparent tectonic rotation, and the structural tilt correction in paleomagnetic studies. *J. Geophys. Res., 85,* 3659-3669.

McKENZIE, D. and J. JACKSON, 1983. The relationship between strain rates, crustal thickening, paleomagnetism, finite strain and fault movements within a deforming zone. *Earth Planet. Sci. Lett., 65,* 182-202.

MINSTER, J. B. and T. H. JORDAN, 1979. Rotation vectors for the Phillipine and Rivera plates. *EOS (Trans. Am. Geophys. Union), 60,* 958 (abstr).

PASQUARÈ, G., V. H. GARDUÑO, A. TIBALDI and M. FERRARI, 1988. Stress pattern evolution in the central sector of the Mexican volcanic belt. *Tectonophysics, 146,* 353-364.

RON, H., R. FREUND, Z. GARFUNKEL and A. NUR, 1984. Block rotation by strike slip faulting: Structural and paleomagnetic evidence. *J. Geophys. Res., 89,* 6256-6270.

SANCHEZ-RUBIO, G., 1984. Cenozoic volcanism in the Toluca-Amealco region, central Mexico. M. Sc. Thesis, Imperial Collage Sci. Tech., Univ. London, United Kingdom.

SILVA-MORA, L., 1979. Contribution à la connaissance de l'axe volcanique Transmexicain: Étude géologique et pétrologie des lavas du Michoacán Oriental. Doc. Ing. Thèse, Univ. Marseille, France.

SOLER-ARECHALDE, A. M., 1990. Paleomagnetismo de la región de Acambay, Faja volcánica Transmexicana. M. Sc. Thesis, National A. Univ. México.

SOLER-ARECHALDE, A. M. and J. URRUTIA-FUCUGAUCHI, Block rotations in a normal/strike-slip fault system-Palaeomagnetic study of the Acambay graben, central Trans-Mexican volcanic arc, (submitted)

SUTER, M., 1990. State of stress and active deformation in Mexico and western Central America. *In:* The Geology of North America, v. DMV 1, Neotectonics of North America.

SUTER, M., O. QUINTERO and C. JOHNSON, 1992. Active faults and state of stress in the central part of the Trans-Mexican volcanic belt. Part 1: The Venta de Bravo Fault. *J. Geophys. Res., 97,* 11,983-11,993.

URBINA, F. and H. CAMACHO, 1913. La zona megasísmica Acambay-Tixmadeje, Estado de México, conmovida el 19 de noviembre de 1912. *Bol. Inst. Geol. Mex., 32,* 125 pp.

URRUTIA-FUCUGAUCHI, J., 1979. Preliminary apparent polar wander path for Mexico. *Geophys. J. R. Astr. Soc., 56,* 227-235

URRUTIA-FUCUGAUCHI, J., 1984. On the tectonic evolution of Mexico: paleomagnetic constraints. *In:* R. Van der Voo, C. R. Scotese and N. Bonhommet (Eds.) Plate Reconstruction from Paleozoic Paleomagnetism. *AGU Geodyn. Ser., 12,* 29-47.

URRUTIA-FUCUGAUCHI, J. and H. BÖHNEL, 1988. Tectonics along the Trans-Mexican volcanic belt according to palaeomagnetic data. *Phys. Earth Planet. Inter., 52,* 320-329.

WERNICKE, B., E. J. SPENCER, B. C. BURCHFIELD and L.P. GUTH, 1982. Magnitude of crustal extension in the southern Great Basin. *Geology, 10,* 499-502.

Ana María Soler Arechalde and Jaime Urrutia Fucugauchi

Laboratorio de Paleomagnetismo y Geofísica Nuclear,
Instituto de Geofísica, UNAM,
Circuito Exterior, Ciudad Universitaria.
04510 MEXICO,D.F., MEXICO.