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PALAEOMAGNETISM AND TECTONICS OF MEXICO

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RESUMEN

Los resultados paleomagnéticos para México, que cubren el intervalo del Cambro-Ordovícico al Neogeno, se revisan y discuten brevemente en términos de los modelos tectónicos regionales propuestos para la evolución de México. Si se consideran las paleo-reconstrucciones de tectónica de placas para las márgenes continentales del Atlántico y la diversidad de bloques o terrenos con diferentes historias tectonoestratigráficas que conforman la estructura continental de México, se esperaría un registro paleomagnético cuyas direcciones y polos mostrarían una divergencia angular creciente con respecto a Norteamérica, en razón directa de su edad.

Las discordancias paleomagnéticas observadas en tal caso podrían ser similares a las documentadas para el cinturón orogénico cordillerano. Sin embargo, estas espectativas no se cumplen. Muchos polos paleozoicos para México se localizan en posiciones cercanas a los polos esperados con respecto a Norteamérica, mientras que la mayoría de los polos cenozoicos divergen de sus polos esperados. Si se consideran varias alternativas que incluyen soluciones tectónicas y no tectónicas, los resultados para el Mesozoico y Cenozoico son diferentes de los observados dentro del Cinturón Orogénico Cordillerano, lo cual sugiere una evolución tectónica diferente para su continuación meridional. Los datos paleomagnéticos son en general congruentes con los modelos que implican movimientos laterales izquierdos de ciertas porciones de México; sin embargo, la evolución tectónica de México parece ser en general más compleja de lo que previamente se había supuesto.

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ABSTRACT

Palaeomagnetic results for Mexico which cover the interval from the Cambro-Ordovician to Neogene are reviewed and briefly discussed in terms of regional tectonic models proposed for the evolution of Mexico.

Following plate tectonic reconstructions of Atlantic bordering continents and the diversity of blocks or terranes shaping Mexico with distinct tectono-stratigraphic histories, one may expect a palaeomagnetic record for Mexico in which directions and poles show an increasing angular divergence going back in time with respect to those of stable North America. This would imply that the palaeomagnetic discordances should be similar to those documented for the Cordilleran Orogenic Belt. This 'expected' record is however not observed. Instead, many Palaeozoic poles for Mexico lay close to the corresponding North American poles, whereas most Cenozoic poles diverge from the corresponding North American poles. Several alternatives, including both tectonic and non-tectonic explanations, are considered. The Mesozoic and Cenozoic palaeomagnetic results from Mexico are different from those observed to the north within the Cordilleran Orogenic Belt, suggesting a distinct tectonic evolution for the southern portion of the orogenic belt. Palaeomagnetic data are in general consistent with models implying regional left-lateral motion of parts of Mexico. The tectonic evolution of Mexico however seems more complex than previously predicted.

INTRODUCTION

Most of Mexico was affected by orogenic deformation during Late Cretaceous-Early Tertiary, and the geological characteristics and structural trends are similar to those observed to the north within the western Cordilleran Orogenic belt (King, 1969, 1977; de Cserna, 1961). Additionally, large areas along the western margin of Mexico are covered by Mesozoic-Cenozoic igneous rocks which form elongated provinces of magmatic arc association (e.g. Sierra Madre Occidental, Trans-Mexican volcanic belt, Sierra Madre del Sur, and Chiapanecan arc), which suggest that plate subduction has been a dominant tectonic control at least since the Late Jurassic (Atwater, 1970; Urrutia-Fucugauchi, 1978, 1986). The young volcanic cover and deformation make it difficult to identify and characterize earlier pre-Mesozoic tectonic events such as those documented in the Appalachian, Ouachita and Marathon orogenic belts of eastern North America. Nevertheless, a possible continuation of the Late Palaeozoic european deformation system, known as the Huastecan structural belt has been recognized (de Cserna, 1960, 1976). It may be interpreted as the product of continental collision between North America, Africa and South America (Wilson, 1966), but timing, location and sequence of events are still being studied. Most global palaeoreconstructions of the Atlantic bordering continents for the Late Palaeozoic - Early Mesozoic show a major overlap of South America onto Central America and southern Mexico (Carey, 1958, Walper and Rowett, 1972), thus implying that these portions which contain Precambrian and Palaeozoic rock units were located elsewhere, relative to cratonic North America.

Definition of the arrangement of the major continental blocks and their subsequent separation is critical for the study of the tectonic evolution of Mexico, Central America, the Gulf of Mexico and the Caribbean. The Gulf of Mexico may have been formed by the drifting apart of North and South America (Walper and Rowett, 1972; Pilger, 1978), or by microblock rotation of units such as the Yucatan peninsula (Carey, 1958; Freeland and Dietz, 1971). Northern Mexico may have come into position by large-scale left-lateral motion along a fault system (e.g. Silver and Anderson, 1974; Pilger, 1978; Urrutia-Fucugauchi, 1981a, 1984), or by a more complex mechanism involving accretion as well as left and right-lateral translations.

Such tectonic motions imply that most of Mexico is allochthonous, and may consist of a 'collage' of blocks or terranes with distinct tectonic and stratigraphic histories. Similar tectonic phenomena may be presently observed; for instance, the Baja California peninsula is moving northwards along the right-lateral San Andreas fault system, and oceanic plateaus (e.g. the Tehuantepec ridge) are being consumed beneath southern Mexico and may eventually be partly accreted to the continental margin. The present configuration of small plates (Cocos and Rivera) off the western margin, and the complex motion pattern (e.g. oblique convergence, transform motion, and spreading center reorganization) indicate past major tectonic events such as the subduction of portions of the spreading center, plate fragmentation and migration of triple junctions (Atwater, 1970; Menard, 1978; Mammerickx and Klitgord, 1982; Urrutia-Fucugauchi, 1978, 1986).

In a simple scenario, one may expect a palaeomagnetic record for Mexico, in which angular divergence between directions and poles of Mexico and those corresponding to 'stable' North America will increase with time from the Recent to the Palaeozoic.

In particular for pre-Triassic times, the major overlap of South America onto southern Mexico (Bullard *et al.,* 1965) and northern Mexico (Walper and Rowett, 1972) implies that the Mexican palaeomagnetic record should be different from that of North America. This information may, in turn, permit the estimation of past positions and relative movements of tectonic blocks from Mexico. Additionally, the orogenic deformation which has affected most of Mexico at various times, and the possibility that most of the country consists of a collage of terranes with distinct tectonostratigraphic histories, also suggest that the palaeomagnetic directions and poles for different rock units of Mexico from distinct tectonic terranes may also show increasing angular divergences with time.

This 'simple' palaeomagnetic record for Mexico is however not being documented and instead, discordant palaeomagnetic results for the Tertiary (e.g. Urrutia-Fucugauchi, 1981a; Bobier and Robin, 1983), and concordant palaeomagnetic results for the Palaeozoic (e.g. Gose and Sánchez-Barreda, 1982; Urrutia-Fucugauchi and Morán-Zenteno, 1985; McCabe *et al.*, 1984) have been reported.

The purpose of this paper is to review the palaeomagnetic data available for Mexico and to briefly discuss major tectonic implications in terms of proposed regional tectonic models and distribution of tectono-stratigraphic terranes.

PALAEOMAGNETIC DATA

Palaeomagnetic results for times older than Neogene and meeting minimum reliability conditions in terms of number of sites, laboratory treatment (detailed demagnetization tests), and statistical parameters, which correspond to the A** category of Irving *et al.* (1976) are considered for this discussion (Table 1).

The limited data base does not permit investigating on the possible arrangement of tectonic units or terranes, so a simple approach of comparing individual directions and pole positions with appropriate reference data from cratonic North America (Irving, 1979), in the proposed tectono-stratigraphic terrane distribution framework, is adopted. In order to test whether any significant declination or inclination anomalies are present, the parameters R (rotation) and F (flattening), as well as their 95% confidence limits (DELTA R and DELTA F), have been calculated (Table 1).

Observed and expected directions from Table 1 are represented in the tectono-stratigraphic terrane map adopted from Campa-Uranga and Coney (1983) and IMP-INEGI (1984) (Fig. 1).

The palaeomagnetic data in Table 1 have been divided according to the proposed terrane distribution (including the overlap assemblages or 'superjacent' terranes of Campa-Uranga and Coney (1983), like the Sierra Madre Occidental and the Trans-Mexican volcanic belt).

Pole positions for the Cenozoic of Mexico are illustrated in Figure 2, and those for the Mesozoic are illustrated in Figure 3. Pole positions for the Tertiary are left-handed and slightly far sided, forming two main groups which correspond to the

MAP.No.	AGE	SAMPLED UNIT	LOCATION	Do	Io	ALPHA 95	Dx	Ix	A 95	R	DR	F	DF	REF.No
CABORCA TERRANE														
18	Trs-Ji	Antimonio Fm.	30.7/-112.5	350.0	33.8	12	350.6	20.4	6	-0.6	15.7	-13.4	16.2	2
							351.5	27.3	6	-1.5	15.8	-6.5	15.7	
CHIHUAHUA TERRANE														
5	Eocene	Chih. volc.###	28.6/-105.8	154.6	-46.6#	4	350.0	47.1	5	-15.4	8.1	0.5	7.2	13
COAHUILA TERRANE														
10	Ku	Difunta Group.	26.0/-101.0	325.0	38.3	12	337.1	52.1	8	-12.1	18.1	13.8	14.7	9
CORTEZ TERRANE														
1	Pliocene	Plioc. Muds.	31.0/-115.0	41.0	43.0	10	358.2	53.0	12	42.8	19.9	10.0	16.0	11
GUERRERO TERRANE														
2	Oligocene	S.M.Occ.Volc###	24.0/-105.0	151.9	-37.1#	10	355.6	41.7	5	-23.7	13.7	4.6	12.0	10
3	Oligocene	Tepalcates-Navios Volc.###	24.0/-105.1	157.5	-34.5#	11	355.6	41.7	5	-18.1	14.5	7.2	12.9	5
4	Lower T.	Jalisco Volc.###	20.7/-102.3	335.6	36.2	10	355.7	36.8	5	-20.1	13.5	0.6	12.4	17
6	Olig-Mio.	Sin-Dgo Volc.###	24.0/-106.0	335.8	33.7	10	355.6	41.8	5	-19.8	13.2	8.1	12.0	1
7	Ku-Tl	Sin. Volc-Int.	24.0/-106.0	3.3	34.9	9	338.2	52.0##	8	25.1	14.5	17.1	12.4	1
							346.4	47.3	7	16.9	13.6	12.4	12.3	
							350.3	43.9	5	13.0	12.3	9.0	11.0	
OAXACA TERRANE														
36	Alb-Cen.		16.6/-97.0	348.7	23.0	7	338.3	37.3	4	10.4	8.7	14.3	9.1	14
40	Pen-Perm.	Fm.Yododene	17.5/-97.2	152.9	24.1	4	151.3	-34.3	5	1.6	6.9	-10.2	8.6	3
43	Tremadoc.	Fm.Tinu	17.5/-97.2	160.0	24.0	n.a.	151.0	-34.0	n.a.	9.0	n.a.	-10.0	n.a.	7
MAYA TERRANE														
9	Maestrich.	Mendez Fm.	22.3/-98.2	349.1	27.8	6	340.8	45.2	7	8.3	10.4	17.4	10.6	6

MAP.No	AGE	SAMPLED UNIT	LOCATION	Do	Io	ALPHA 95	Dx	Ix	A95	R	DR	F	DF	REF.No
37	Kl	Sn.Ricardo Fm.	16.8/-93.7	340.3	19.9	3	340.4	20.7	13	-0.1	13.6	0.8	23.8	5
38	Jm-Ju	Tr-J Red Bed	17.6/-96.3	28.9	-14.0	11	356.5	-0.1##	6	32.4	12.8	13.9	16.3	ined
							356.5	-8.2	6	32.4	12.8	5.8	16.1	
39	lower Permian	Paso Hondo-Grupera Fm.	15.5/-92.5	177.8	0.6	4	153.8	-39.9	6	24.0	7.6	-39.3	9.2	3
MIXTECA TERRANE														
33	Olig-Mio.	Jantetelco-Tepexco.###	18.7/-98.8	301.2	27.1	11	356.9	33.4	4	-55.7	13.1	6.3	12.6	12
34	Olig-Mio.	Gro. Volc.###	18.6/-99.4	144.2	-22.4	9	355.8	33.1	5	-31.6	11.1	10.7	11.9	16
35	Pal-Eoc.	Balsas Fm.###	18.6/-99.0	310.9	16.3	12	350.5	34.3	5	-39.6	13.6	18.0	14.2	16
41	Alb-Cen.	Morelos Fm.	17.7/-99.5	332.7	46.8	4	332.0	49.0	4	0.7	7.5	2.2	6.1	18
44	Pen-Perm.	Olinala Fm.	17.7/-98.7	160.0	0.6	8	344.6	-28.2	7	-4.6	10.8	-28.8	14.1	19
SIERRA MADRE ORIENTAL TERRANE														
11	Apt-Alb.	C.del Cura Fm.	23.8/-99.2	345.1	43.5	3	331.6	49.2	10	13.5	12.3	5.7	11.8	4
12	Jurassic	Nazas Fm.	25.0/-103.5	350.6	28.4	8	335.6	46.4	15	15.0	19.3	18.0	19.9	9
13	Oxford.	Zuloaga Fm.	23.8/-99.2	180.8	-37.5#	2	348.3	28.5	13.	12.5	13.7	-9.0	21.7	4
14	Oxford.	Zuloaga Fm.	23.8/-99.2	349.9	44.4	8	348.3	28.5	13.	1.6	17.5	-15.9	23.0	4
15	Jm-Ju.	La Joya Fm.	23.8/-99.2	124.3	-34.0#	13	334.8	46.9	4	-30.5	16.4	12.9	13.9	4
16	Jm-Ju.	La Joya Fm.	23.6/-99.2	141.5	-23.3	10	334.9	46.7	4	-13.4	11.8	23.4	11.1	4
17	Jurassic?	Huizachal Fm.	23.5/-99.5	330.4	28.9	6	351.8	27.0	12	-21.4	14.2	-1.9	21.2	9
19	Tru	La Boca Fm.	23.5/-99.5	222.9	-30.0	10	355.4	3.9##	6	47.5	13.0	-26.1	15.6	4
							350.6	-8.0	7	52.3	13.5	22.0	17.0	
20	Tru	La Boca Fm.	23.7/-99.8	30.0	17.3#	7	355.2	4.4##	6	34.8	9.5	-12.9	13.8	4
							350.5	-7.6	7	39.5	10.1	-24.9	15.5	
21	Tru	La Boca Fm.	23.8/-99.1	40.8	3.1#	13	355.5	4.5	6	45.3	14.3	1.4	17.7	4
							350.9	-7.6	7	49.9	14.8	-10.7	19.0	
22	Tru	La Boca Fm.	23.8/-99.1	40.0	3.2#	8	355.5	4.5##	6	44.5	10.0	1.3	14.4	4
							350.9	-7.6	7	49.1	10.6	-10.8	16.0	
23	Tru	La Boca Fm.	23.8/-99.1	44.7	27.7#	10	355.5	4.5##	6	49.2	12.8	-23.2	15.6	4
							350.9	-7.6	7	53.8	13.3	-35.3	17.1	
24	Tru	La Boca Fm.	23.8/-99.2	229.4	-25.1	14	355.5	4.5##	6	53.9	16.6	-20.6	18.4	4
							350.8	-7.5	7	58.6	17.0	-32.6	19.7	
25	Tru	La Boca Fm.	23.8/-99.2	284.1	-6.4	6	355.5	4.5##	6	-71.4	8.5	10.9	13.4	4
							350.8	-7.5	7	-66.7	9.3	-1.1	15.1	
26	Tru	La Boca Fm.	23.8/-99.2	275.9	-18.0	6	355.5	4.5##	6	-79.6	8.7	22.5	13.4	4
							350.8	-7.5	7	-74.9	9.4	10.5	15.1	

MAP.No	AGE	SAMPLED UNIT	LOCATION	Do	Io	ALPHA 95	Dx	Ix	AA95	R	DR	F	DF	REF.No
27	Tru	La Boca Fm.	23.8/-99.2	263.8	-18.2	8	355.5	4.5##	6	-91.7	10.3	-13.7	14.4	4
							350.8	-7.5	7	-87.0	11.1	-25.7	16.0	
28	Tru	La Boca Fm.	23.8/-99.2	110.8	-1.2#	9	355.5	4.5##	6	-64.7	10.8	3.3	15.0	4
							350.8	-7.5	7	-60.0	11.4	-8.7	16.5	
29	Tru	La Boca Fm.	23.6/-99.2	141.1	-4.6#	4	355.5	4.5##	6	-34.4	7.2	-0.1	12.6	4
							350.8	-9.9	7	-29.7	8.1	-14.5	14.3	
30	Tru	La Boca Fm.	23.6/-99.2	156.1	-13.3#	7	355.5	4.1##	6	-19.4	9.4	-9.2	13.9	4
							350.8	-9.9	7	-14.7	10.1	-23.2	15.4	
31	Tru	La Boca Fm.	24.7/-100.1	137.1	-47.9#	6	355.1	6.4##	6	-38.0	10.8	-41.5	13.3	4
							350.4	-5.5	7	-33.3	11.4	-53.4	15.1	
TOLIMAN TERRANE														
32	Olig-Mio.	Chichinautzin and Gpe Group ###	19.5/-99.2	179.0	-36.6	13	356.9	34.6	4	2.1	16.8	-2.0	14.3	8
XOLAPA TERRANE														
42	Eocene	Acapulco Gr.	16.5/-99.5	338.0	38.0	10	355.0	37.0		-17.0		-1.0		15

#	Polarity of remanence direction interpreted as reverse in original reference.
##	More poles are given for reference (taken from Irving, 1979 and Van Alstine & de Boer, 1978).
###	Superjacent tectono-stratigraphic terrane.
REF.No.	Number of the reference at the cited reference's list.
n.a.	Not available data.
MAP No.	Number of reference in Fig. 1.
LOCATION	Geographic latitude and longitude of sampling sites.
Do	Observed magnetic declination.
Io	Observed magnetic inclination.
ALPHA 95	95% confidence cone for observed directions.
Dx	Expected magnetic declination according to the reference pole.
Ix	Expected magnetic inclination according to the reference pole.
A 95	95% confidence cone for the reference pole.
R	Rotation parameter.
DR	(Delta R), 95% confidence limit for rotation parameter.
F	Flattening parameter.
DF	(Delta F), 95% confidence limit for flattenning parameter.

TABLE 1.- OBSERVED AND EXPECTED PALAEOMAGNETIC DIRECTIONS

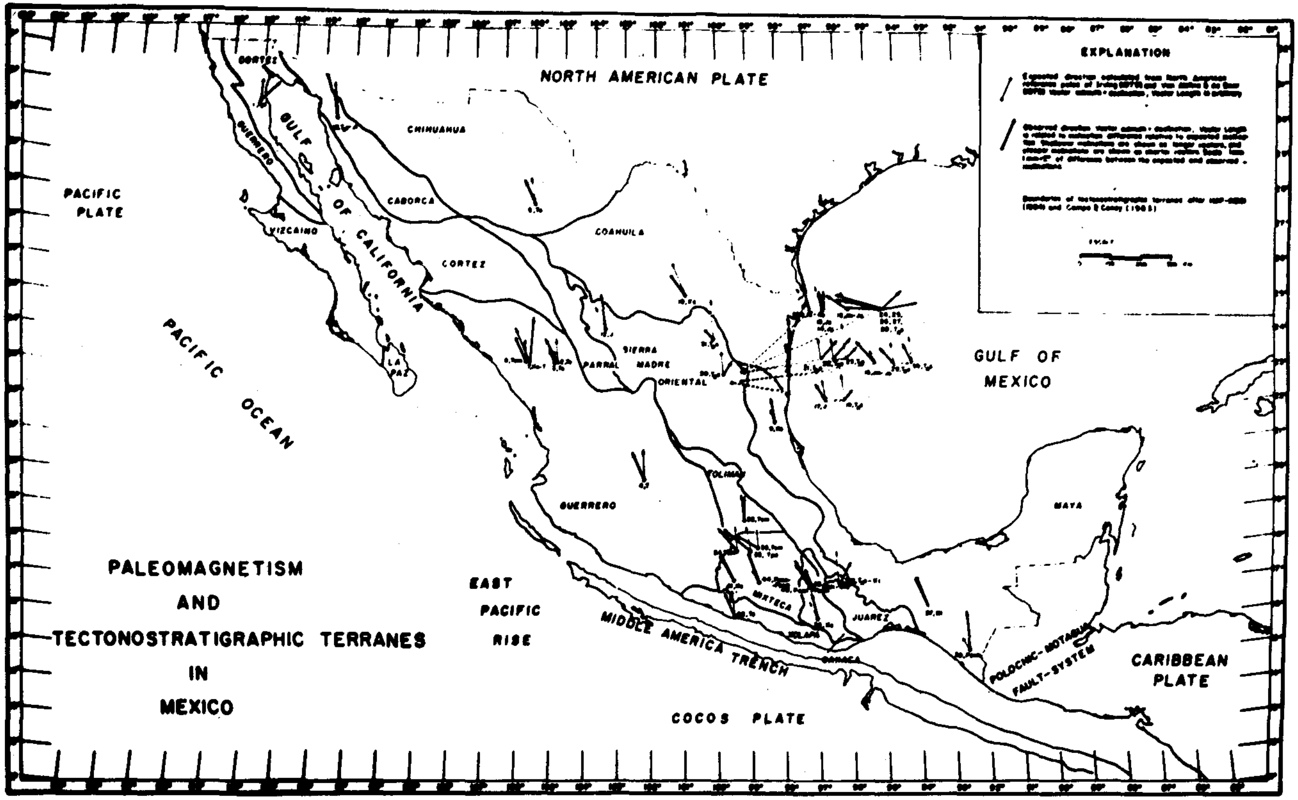


Fig. 1. Schematic representation of available palaeomagnetic results for Mexico. Wide arrows represent observed declinations and narrow arrows represent expected declinations. Magnetic inclinations are illustrated as a relative difference in length between expected and observed directions. Sampled sites are plotted on a map with the tectonostratigraphic terrane distribution of Campa-Uranga and Coney (1983) and IMP-INEGI (1984). Further details on palaeomagnetic data are provided on Table 1, using the same notation.

Sierra Madre Occidental province of northern Mexico (entries 2, 3, 4, 5 and 6, identified by "###" as superjacent tectono-stratigraphic terrane in Table 1, Figure 2), and to central Mexico, within or immediately to the south of the Trans-Mexican volcanic belt (entries 32, 33, 34, and 35, Figure 2). These results show significant negative R values and small positive F values (Table 1), which suggests counterclockwise rotation and small, if any, northward displacement of the studied areas relative to cratonic North America.

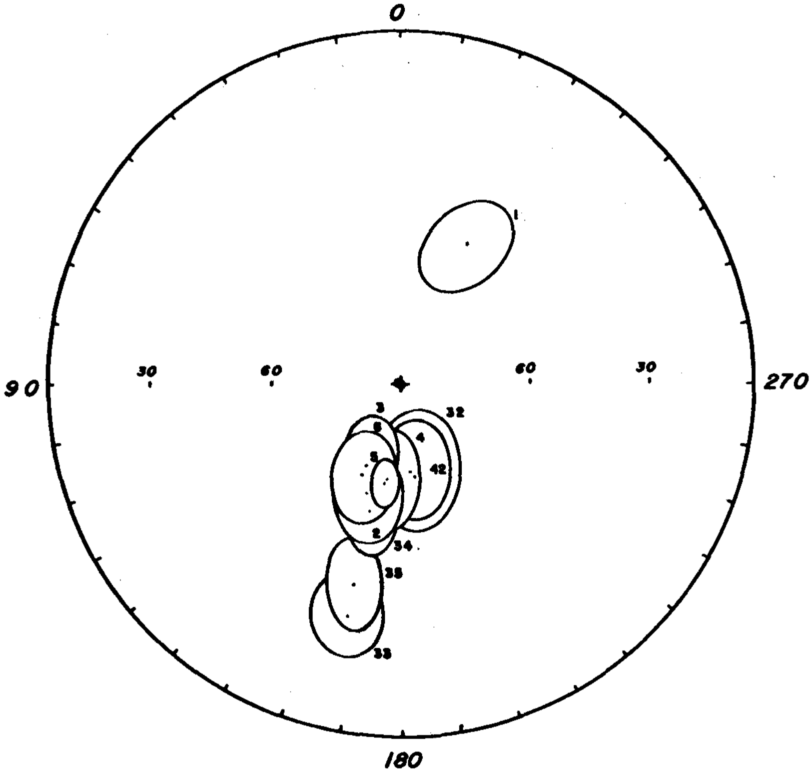


Fig. 2. Cenozoic palaeomagnetic pole positions for Mexico. Nomenclature and site coordinates are given in Table 1.

Palaeomagnetic directions for the Mesozoic and Palaeozoic show a more complex pattern, Cretaceous and Late Cretaceous-Early Tertiary observed directions are quite similar to the expected directions for North America (entries 5, 7, 9, 10, 11, 36 and 37) and statistical errors for R and F parameters are generally higher than the parameter itself.

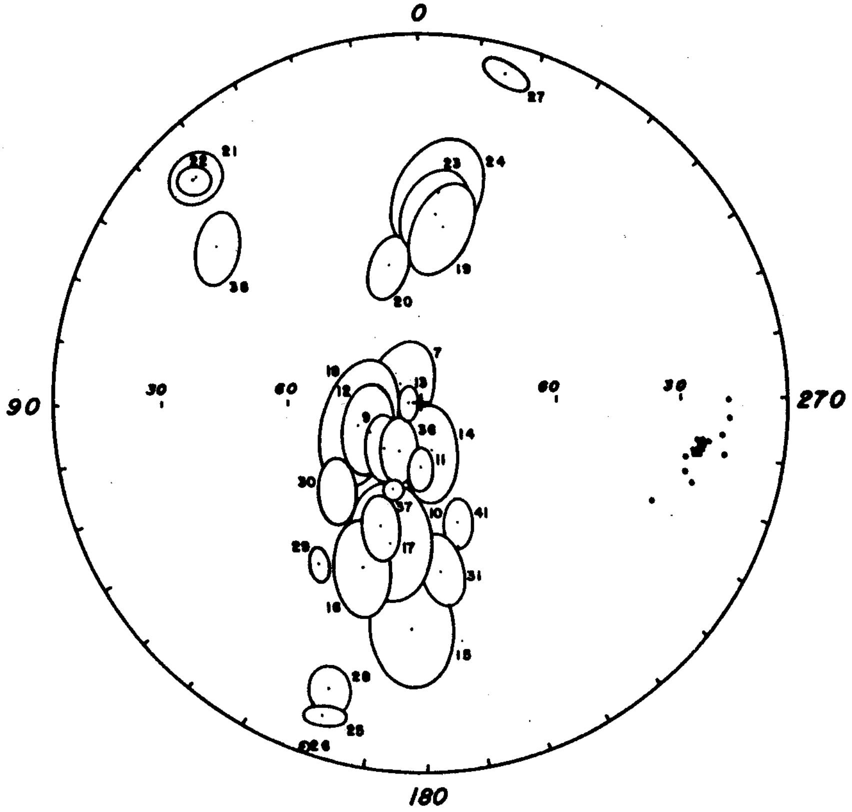


Fig. 3. Mesozoic and Palaeozoic palaeomagnetic pole positions for Mexico. Nomenclature and site coordinates are given in Table 1.

Most Jurassic and Late Triassic - Early Jurassic declinations show left angular divergences with respect to North America (entries 15, 16 and 17), however some other sites have 'right' angular divergences (entries 13, 14 and 38), and even no divergence at all (entries 12 and 18).

The magnetic polarity for the Triassic results is not determined, and it has been suggested (Gose *et al.,* 1982) that they follow a path to the left of the North American APWP (Fig. 4). These Triassic results imply large-scale movements of the studied area (Gose *et al.,* 1982), provided that the angular divergences are due solely to tectonic causes.

Finally, all Palaeozoic directions show an intriguing pattern. Early Permian pole of Chiapas is displaced from its corresponding segment of North American APWP, but lies close to lower Jurassic poles. Tremadocian and Permian observed palaeomagnetic directions (entries 40 and 43), as well as Pennsylvanian-Permian directions from Guerrero in the Mixteca Terrane (entry 44), are close to the expected declinations with respect to North America.

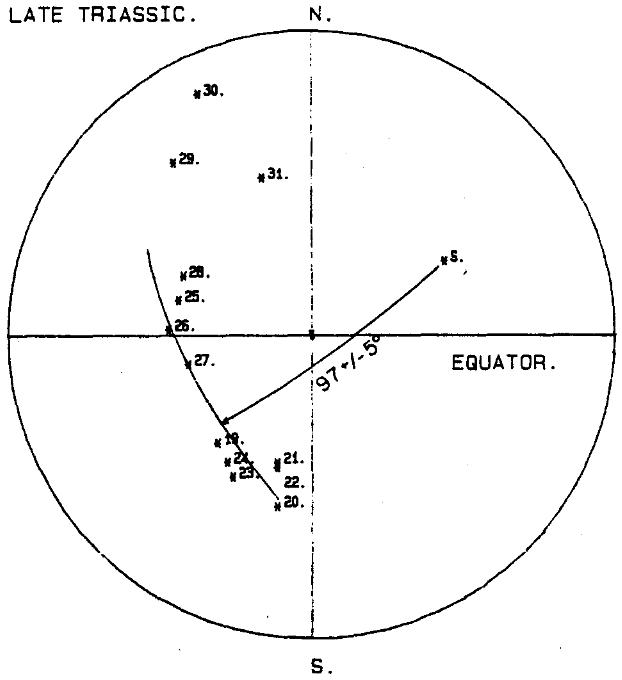


Fig. 4. Upper Triassic pole positions from the Huizachal red beds from northeastern Mexico (nomenclature in Table 1). Note that the pole positions follow an apparent girdle distribution. The small circle fit to the southernmost poles has its center in the sampling areas. This type of distribution may indicate apparent tectonic rotation (MacDonald, 1980). Data are from Gose *et al.* (1982) and Nairn (1976). See text for discussion.

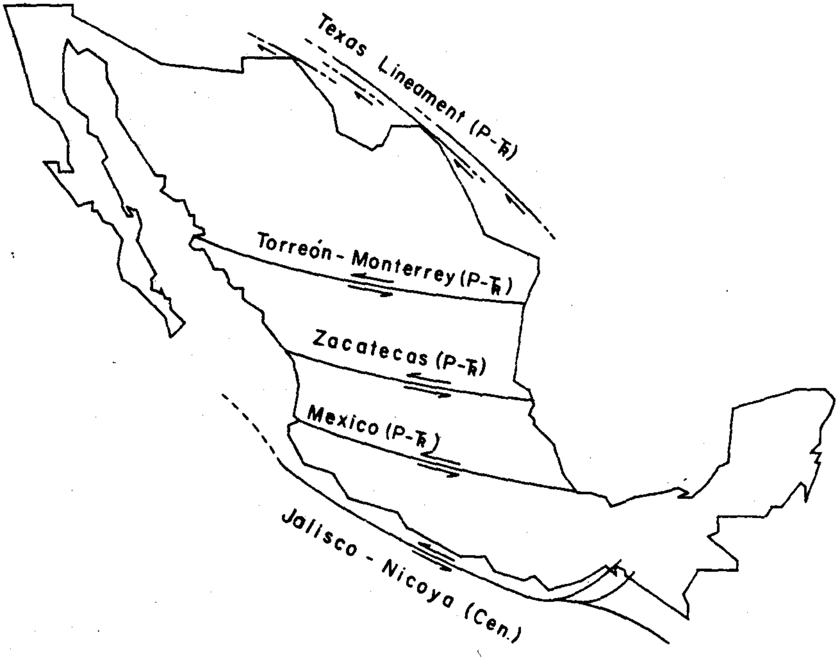
In summary, the distribution of pole positions seems complex, although most poles are displaced to the left of the reference path for North America (Figs. 2, 3 and 4), suggesting counterclockwise tectonic rotation of studied areas relative to cratonic North America (Table 1). However, the apparent exceptions and ambiguities (e.g. undetermined polarity of Triassic results) make interpretation of tectonic implications non unique. In this discussion emphasis is placed on potential problems, alternative explanations and possible regional tectonic significance of the paleomagnetic record.

DISCUSSION

The palaeomagnetic record for the Mesozoic-Cenozoic of Mexico appears different from that documented to the north along the western margin of North America. Most results from the Western Cordillera from California to Alaska are consistently displaced to the right of the reference APWP (Beck, 1976, 1980; Irving, 1979). This discordant palaeomagnetic record has been explained by predominant northward transport and clockwise rotation of tectonic blocks or terranes (which are then allochthonous) in relation to the North American interior (Beck, 1980). In contrast, pole positions reported from Mexico, if discordant, are displaced mostly to the left (Figs. 2, 3 and 4), therefore suggesting a different tectonic evolution for the 'southern' portion of the Cordilleran Orogenic Belt (King, 1969; King, 1977). The results are consistent with predominant left-lateral motion of parts of Mexico, which may have taken place along a major fault system (de Cserna, 1960, 1976; Silver and Anderson, 1974; Walper, 1980; Pilger, 1978; Tardy, 1980; Urrutia-Fucugauchi, 1981a, 1984).

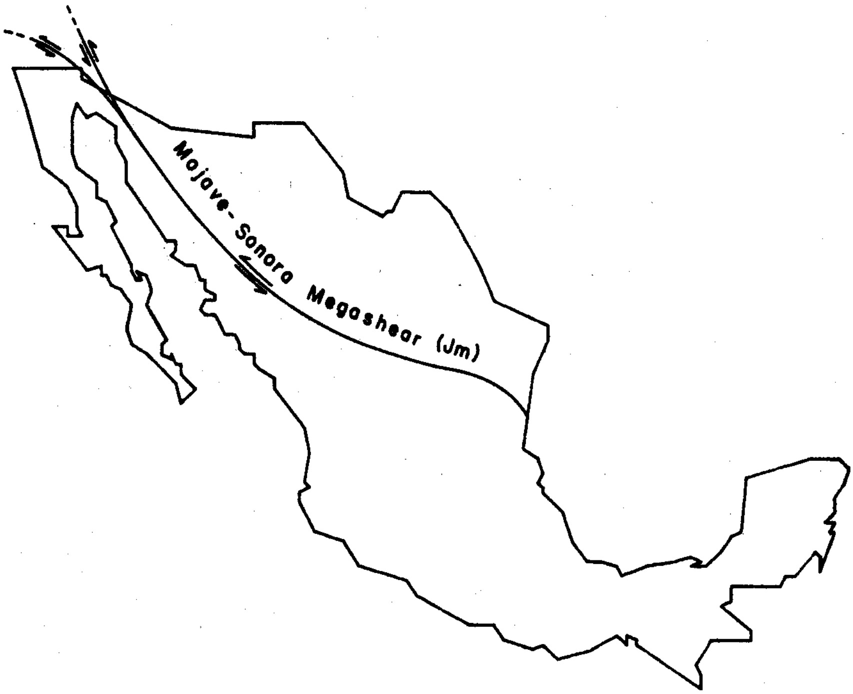
The palaeomagnetic record for the Tertiary shows a consistent pattern with poles forming a very compact group (Fig. 2). The observed directions are systematically displaced to the left of expected directions, all giving significant negative R values (between −15 and −24 degrees for northern Mexico, and between −32 and −56 degrees for central Mexico) and non significant F values (except for entry 35 in Mixteca Terrane, which shows positive F). The pattern seems very consistent, irrespective of the magnetic polarity of the remanences and one may explore a geotectonic explanation.

In recent studies a regional fault system active at present at the western end of the Trans-Mexican volcanic belt has been reported (e.g. Nieto Obregón *et al.*, 1985; Delgado-Granados and Urrutia-Fucugauchi, 1985). Palaeomagnetic results for areas in the Trans-Mexican volcanic belt can be interpreted in terms of local rotations of blocks in response to regional left-lateral shear (Urrutia-Fucugauchi, 1981b, 1983a and b). Mooser (1968, 1972) has mapped a system of *en-echelon* faults crossing central Mexico, which exerts a structural control on the volcanic activity. In the literature, there are many studies documenting rotation of crustal blocks in areas subjected to compressional shear stress (e.g. Freund, 1970, 1974; Fitch, 1972). Palaeomagnetic studies have been successfully used to investigate and quantify local rotations in orogenic areas (e.g. MacDonald and Opdyke, 1972; Beck, 1976; Irving, 1970; Freund and Tarling, 1979; Greenhaus and Cox, 1979; MacDonald, 1980). A summary of some models of tectonic rotation of crustal blocks associated with lateral regional shear is given in Figure 6. Creation of pull-apart basins (Fig. 6d) in response to left-lateral shear may explain major east-west oriented grabens in the volcanic belt such as the Chapala graben (Fig. 5). The 'zig-zag' pattern of the fault system is reflected in the volcanic structures (Mooser, 1972), and it seems likely that such system acts as an efficient structural control for magmas, which may explain why the volcanic belt is not parallel to the trend of the Middle America Trench (Fig. 7) but forms an angle with respect to it of some 15-20 degrees (Molnar and Sykes, 1969).

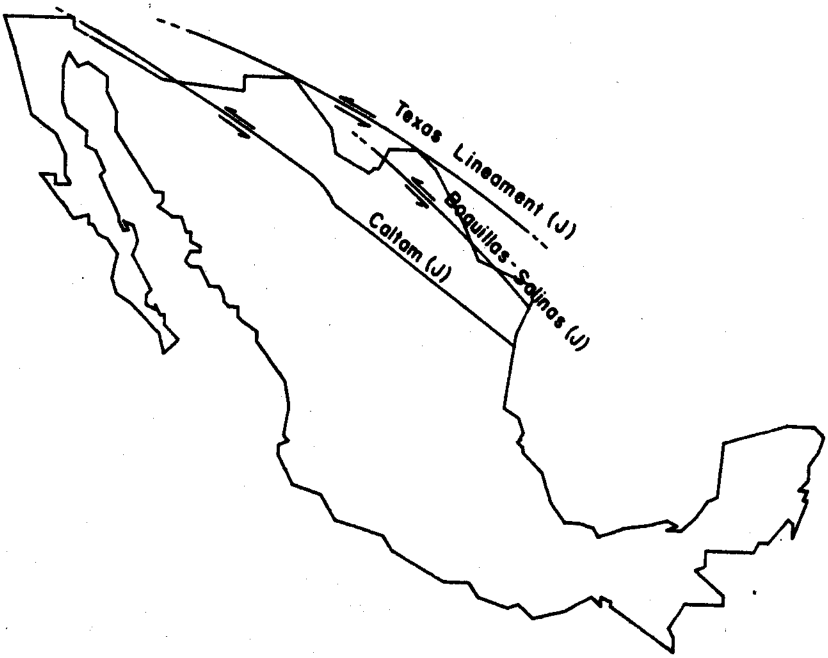


5(a)

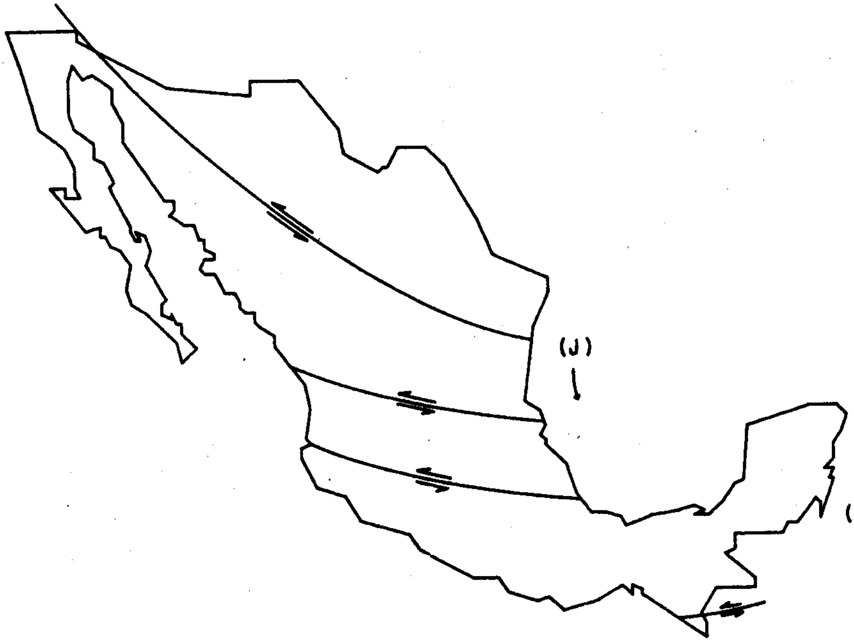
Fig. 5. Summary of tectonic models for the evolution of Mexico which involve major lateral strike slip displacements. Figures are modified and adopted from the following works: a) de Cserna (1971, 1976); b) Silver and Anderson (1974) and Cohen *et al.* (1982); c) Tardy (1980); d) Pilger (1978); e) Mooser (1972, 1975); f) Gastil and Jensky (1973), g) Walper (1980) and h) Viniegra (1971).


Mojave-Sonora Megashear (Jm)

5(b)

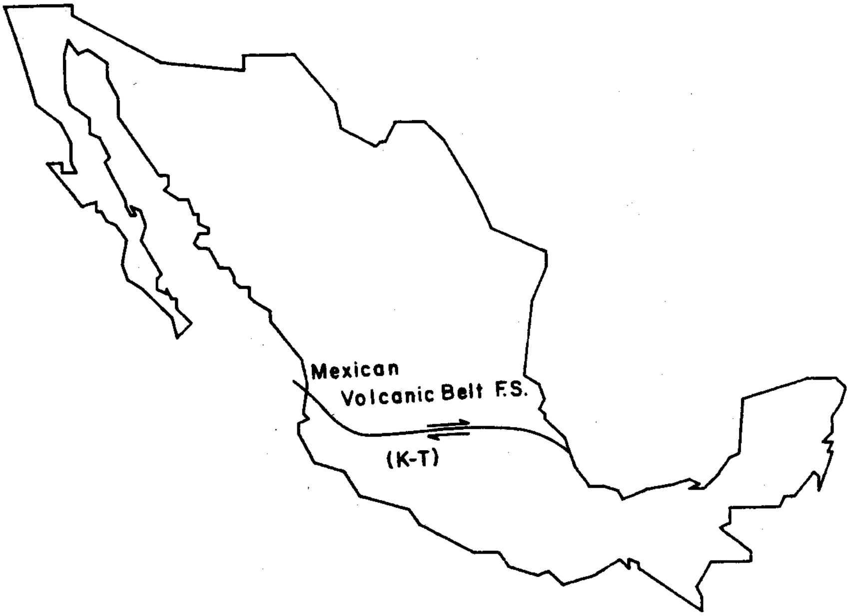

Texas Lineament (J)
Boquillas-Sabinas (J)
Caltam (J)

5(c)

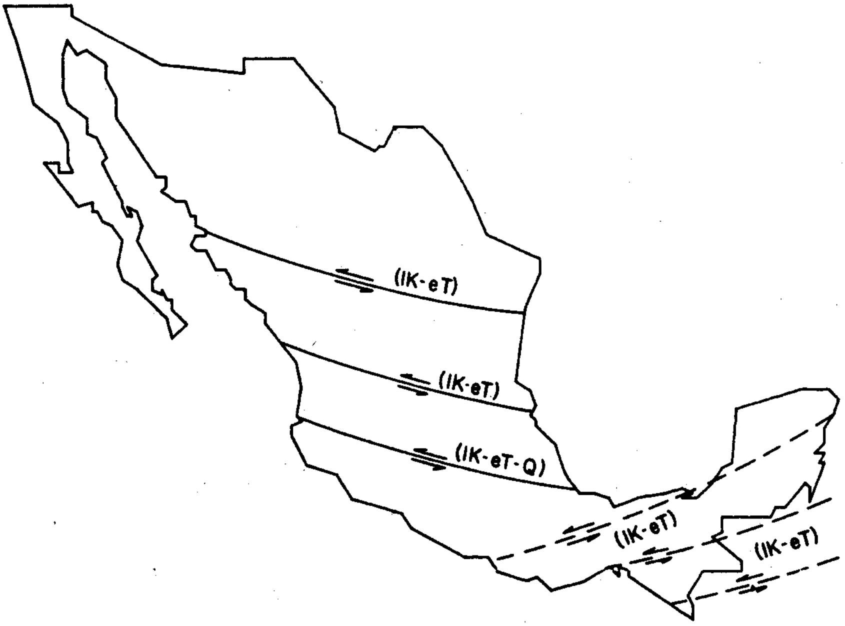


5(d)

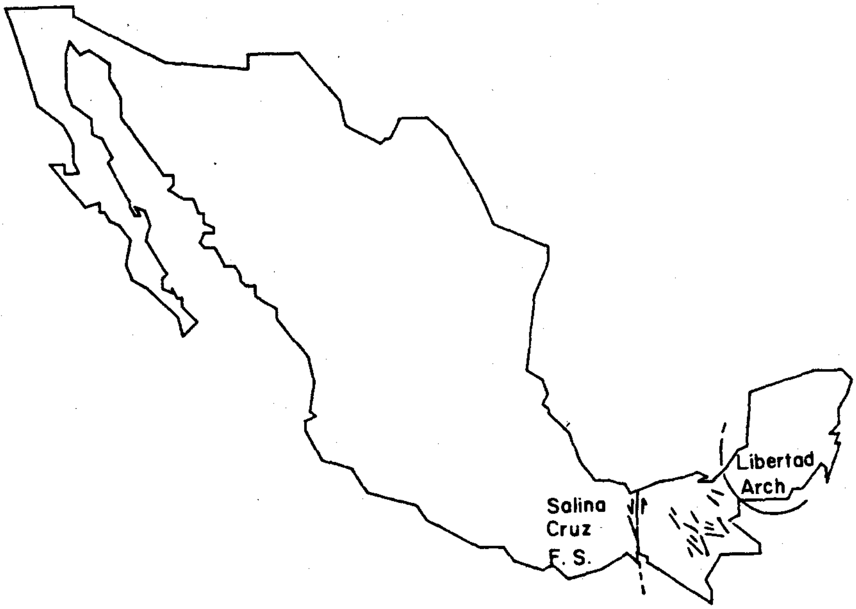
5(e)



5(f)



5(g)



5(h)

Mauvois (1977) has proposed large-scale *nappe* folding and faulting in post-Miocene time. In areas such as that of Morelos State (site of entry 33, Fig. 2), the Cretaceous limestones are overlying Miocene volcanic rocks (Mauvois, 1977).

Suggestions for active lateral regional shear along the volcanic belt based on seismic studies have been proposed by some authors (e.g. Figueroa-Abarca, 1964; Martin and Case, 1975). Some earthquakes like the 11 March 1967 in the Gulf of Mexico show some left-lateral strike slip motion (Molnar and Sykes, 1969), but other large earthquakes in the belt show focal depths much larger, being intermediate-depth earthquakes and focal mechanisms like those of southern Mexico to the south of the volcanic belt (e.g. Molnar and Sykes, 1969; Dean and Drake, 1978).

The palaeomagnetic results for northern Mexico show smaller but very consistent angular divergences (Table 1). Studied units are part of the Sierra Madre Occidental volcanic province, which corresponds to an overlapping assemblage or superjacent terrane. The very consistent discordance may reflect a geomagnetic cause, e.g. (1) a regional long-term assymetry of the magnetic field; (2) an apparent polar wander movement, where the North American poles used in the curve are not representative of the palaeomagnetic field for the lower Tertiary; or (3) a regional tectonic rotation of northern Mexico. Local rotations of crustal blocks in response to regional lateral shear along fault systems seems easier to accomodate with geologic-tectonic models for the evolution of this northwestern Mexico magmatic arc province.

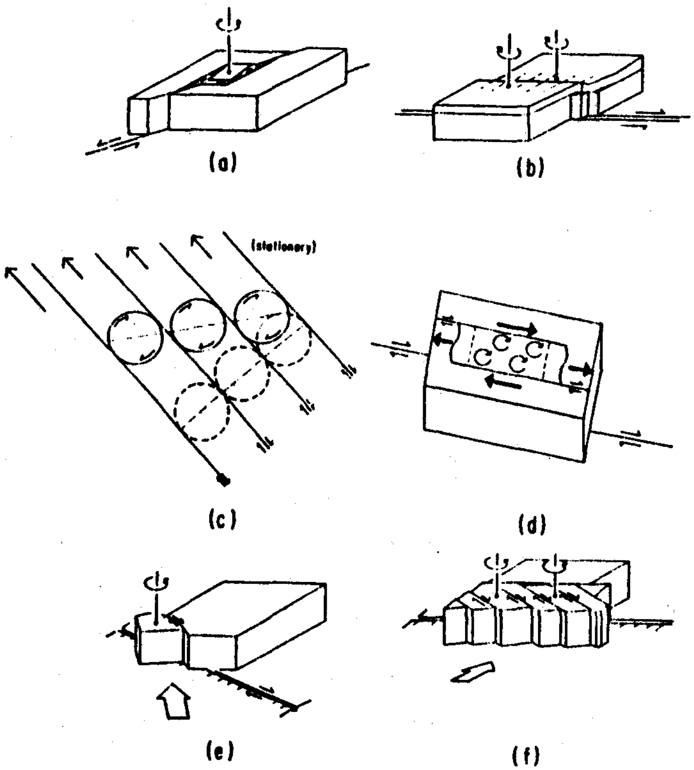
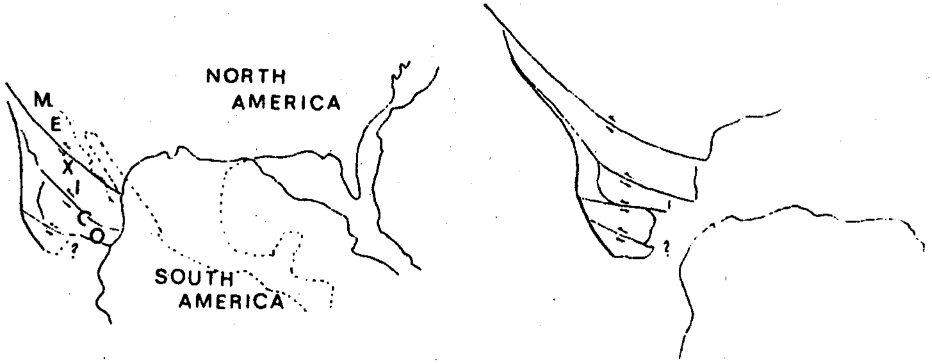


Fig. 6. Summary of models proposed for tectonic rotation of crustal blocks associated with lateral regional shear (modified after MacDonald, 1980 and Beck, 1976).

Plate subduction was a dominant tectonic process at the western margin, and major plate re-organization events (e.g. Atwater, 1970; Menard, 1978) may have certainly resulted in deformation of the continental margin. Field tests on the existence and age of proposed left-lateral faulting in northern Mexico is needed in order to evaluate the palaeomagnetic results. McKee *et al.* (1984) recently reported results of structural-stratigraphic study supporting Mesozoic and Tertiary faulting within a 280 km long W-NW zone in Coahuila, Mexico, parallel to the Mojave-Sonora megashear.

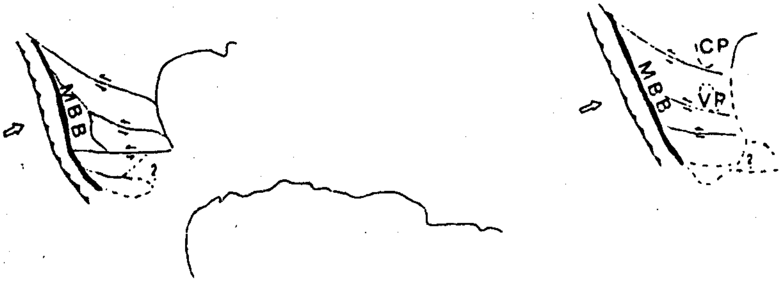
a) Permian

b) Late Triassic



c) Late Jurassic

d) Late Cretaceous



e) Early Tertiary

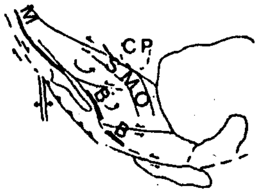


Fig. 7. Schematic representation of tentative evolution of the Gulf of Mexico - Central America since the Permian. Reconstruction of relative positions of major blocks is after Ladd (1976) and Van der Voo *et al.* (1976). Symbols are CP, Coahuila peninsula; VP, Valles platform; MBB, Mesozoic batholith belt; SMO, Sierra Madre Oriental. See text for details.

Results for the Mesozoic complicate the pattern; Cretaceous directions show no tectonic significant divergences. Jurassic and Late Triassic-Early Jurassic directions, if discordant, present a mixed pattern of positive and negative R values (Table 1).

Still some geographic distribution may be observed, particularly within the deformed area of the Sierra Madre Oriental in northeastern Mexico and along the trace of the Sonora-Mojave megashear (Fig. 5). With respect to the latter Silver and Anderson (1974) proposed 800 km of left-lateral displacement occurring during the Middle Jurassic along the megashear. Results from the Antimonio Formation of Sonora (entry 18) have been interpreted by Cohen *et al.* (1982) in support of the megashear model. The observed angular divergence is however within the statistical uncertainties of the results (the pole position lies within the Lower Jurassic segment of the North American APWP; Fig. 3). It is also of interest to mention that the lower part of the Antimonio Formation contains marine fossils (ammonoids) of Upper Carnian age which may be assigned to the Hallstatt facies (King, 1969; Tozer, 1982). If this interpretation is correct, then this constitutes the only known Hallstatt facies locality of western North America, Tozer (1982) has proposed a low latitude (equatorial) palaeoposition for the terrane off the coast of western Mexico, and suggested that it may have come to its present relative position during the Jurassic, and suggested that this terrane should be very likely allochthonous; however, according to paleolatitudinal maps (Irving, 1979) for 225 m.a. (Carnian age), the Antimonio Formation should be in almost equatorial position, which does not support this interpretation. González-León (1980) has recognized strong lithologic and faunistic similarities between Antimonio Formation and Triassic Luning Formation from Pilot Mountains of Nevada, and suggested that El Antimonio Triassic-Jurassic sequence may be the southern prolongation of a Late Triassic-Early Jurassic sedimentary belt which is distributed along the western margin of North America. The palaeomagnetic results for the Antimonio Formation do not seem to support the concept of an accreted terrane which traveled long distances, but further palaeomagnetic results are required to investigate on this possibility.

The palaeomagnetic results for the Sierra Madre Oriental in the area around Monterrey City, where the orogenic belt is bent from almost N-S trend to E-W present a complex pattern (Fig. 1). Gose *et al.* (1982) interprets the results in terms of a large 130 degrees counterclockwise tectonic rotation of northern Mexico with respect to North America. The magnetic polarity of the units is not determined, and Gose *et al.* (1982) interprets the results to produce an apparent polar wander segment across the Pacific Ocean (Fig. 4). This distribution is similar to the type interpreted by MacDonald (1980) in terms of apparent tectonic rotation. Following this author, we have fitted a small circle to the distribution of Triassic poles, and found a good fit with a center in the sampling area (Fig. 4), in good agreement to MacDonald's suggestion. It seems easier to interprete the results in those terms, and to accept a tectonic model with smaller movements with dominant left-lateral motion of parts of Mexico (e.g. Fig. 5), along the major systems of faults (de Cserna, 1976; Silver and Anderson, 1974; Tardy, 1980). Conclusive evidence in support of extensive left-lateral movement is lacking, but some stratigraphic and structural studies have documented histories of recurrent left-lateral movements along segments of the fault system (e.g. Tardy, 1980; Charleston, 1981; McKee *et al.*, 1984).

According to palaeoreconstructions for the Permo-Carboniferous of North and South America, the Precambrian and Palaeozoic terranes of southern Mexico and northern Central America should have been located elsewhere relative to cratonic North America (Carey, 1958; Bullard *et al.*, 1965; Walper and Rowett, 1972; Van der Voo *et al.*, 1976; Pilger, 1978; Walper, 1980). Instead, the Permo-Carboniferous pole for Oaxaca Terrane (entry 40, Fig. 3) which lies close to the corresponding segment of the North American APWP suggests a relative position similar to the actual one. This interpretation seems rather paradoxical, taking in account Mexico-South America overlap in Bullard's Pangea, and proposals for displacements along left-lateral faults (Fig. 5). The sampling site is located in a tectonic terrane characterized by Precambrian metamorphic rocks of Grenville age of the Oaxaca complex (Fries *et al.*, 1966). The metamorphic rocks are unconformably covered by sedimentary units of the Tiñu Formation (Cambrian-Silurian), as well as the Ixtaltepec, Santiago and Yododeñe Formations (Mississipian-Permian). Trilobite fossils found in the lower part of the Tiñu Formation (Pantoja-Alor and Robinson, 1967) have been correlated with the Olenid-Ceratopygid faunal province, which is different from the Rasettia Highatelia province, characteristic of North America (Whittington and Hughes, 1974; Keppie, 1977).

The Oaxaca terrane in southern Mexico is limited by the Mixteca terrane (to the west), Xolapa terrane (to the south), and the Juarez terrane (to the east). The contact between the Oaxaca and Mixteca terranes is characteristic of a suture zone (Ortega-Gutiérrez, 1981), and the collision between the two terranes may have occurred during the Early Devonian, contemporaneous with the closure of the proto-Atlantic ocean (Fig. 8).

The Mixteca terrane basement (Acatlán complex) is formed by a metamorphic complex including metapelites, migmatites, metaophiolites and mylonitized granitoids with Ordovician-Devonian radiometric dates (Ortega-Gutiérrez, 1981). The possibility of a North Appalachian provenance for the Acatlán Complex has been suggested. This is supported by the presence of Taconian and Acadian orogenic phases and related petrotectonic suites (Ortega-Gutiérrez, 1981). The palaeomagnetic record of the Permian sedimentary sequence overlying the Acatlán Complex in the Mixteca terrane (entry 44) gives a pole in close position (Fig. 2) to the corresponding segment of the apparent North American APWP. A possible explanation may be that the composite Mixteca-Oaxaca terrane may have been accreted to southern Mexico after Permo-Triassic times, due to a movement along the same

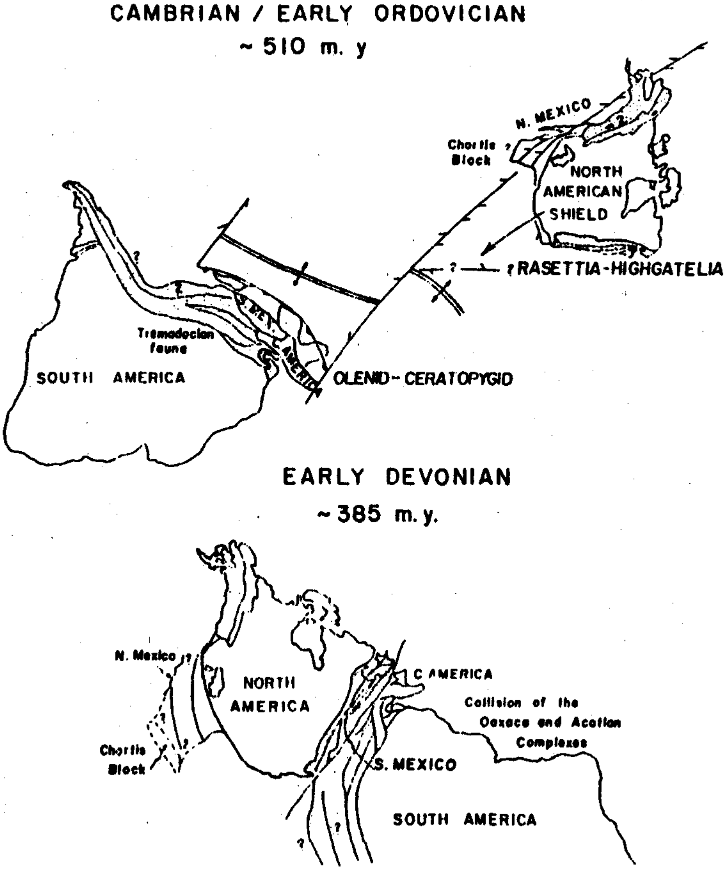


Fig. 8. Schematic representation of tentative paleo-reconstructions. Major continental masses for the a) Cambrian - Early Ordovician, and b) Early Devonian, depicting the position of the Oaxaca and Acatlán terranes of southern Mexico (modified from Keppie, 1977).

palaeolatitude. However, a more plausible explanation might be the remagnetization of palaeozoic sequences (Olinalá and Tiñu Formations, entries 44 and 43). This could be consistent with proposals for displacements along Mesozoic left-lateral faults. Preliminary palaeomagnetic results for Callovian Yucuñuti Formation within Mixteca Terrane shows observed declination to the left and higher inclination than its corresponding expected reference pole (González-Torres *et al.*, 1986).

For Late Palaeozoic, and before Gondwana-Old Red Continent collission, both terranes might have reached a Pacific position by a still not well understood tectonic process. Faunal affinity between Permian sequences of the Antimonio area (Sonora) and Olinalá area (Guerrero), suggests a Pacific position for the Mixteca terrane since that time. Furthermore, recognition of *Neuqueniceras, Xenocephalites* and *Eurycephalites* genera species in the Middle Jurassic sequence of this terrane (Imlay, 1980), also suggests a Pacific origin of marine transgressions. For Westerman and coworkers (1984), the *Neuqueniceras* genera association is similar to the *Neuqueniceras* association of contemporaneous Andean sequence of South America. In the event that the Mixteca terrane was located along the northwestern Mexican margin, as suggested, the palaeolatitude range would be similar to the Andean sequences of the Southern hemisphere. Another line of evidence of the Mesozoic Pacific affinity of this terrane is the marine character of some Middle Jurassic sequences while in the Gulf of Mexico region only evaporitic sequences have been interpreted for Callovian times. Mixteca-Oaxaca composite terrane may have been tectonically transported from a northwestern region relative to its actual position. This Middle Jurassic-Early Cretaceous movement could have been not as straightforward as it might be thought. An alternative explanation for interpreting the palaeomagnetic record for Jurassic-Cretaceous times is in terms of a two phase tectonic transport: the first would have a southeastward component, associated with some latitudinal movement during Middle to Late Jurassic, which is shown on the preliminary results from Yucuñuti Formation (González-Torres, 1986), and the second phase would be a net eastward movement during Early Cretaceous times along the same latitude. This last phase of movement could not be palaeomagnetically recorded and would yield results such as those obtained for Early Cretaceous Formations (entries 36 and 41). A tectonic transport and further accretion of a Pacific affinity terrane onto a terrane of Atlantic (Gulf of Mexico) affinity would develop a cretaceous volcanic arc and intensive crustal shortening (e.g. the Sierra de Juárez, Carfantan, 1983).

The lower Permian pole for Chiapas (entry 39, Fig. 3), lies far from the Oaxaca pole (entry 40), but it lies close to the Lower Jurassic segment of the North American APWP pointing out the possibility of a remagnetization. Providing that the remanence is Early Permian, Gose and Sánchez-Barreda (1982) suggested a palaeoposition for Chiapas just off northern Baja California, which would be in agreement with the reconstruction of Figure 8a. Alternatively, these authors suggested that if remanence is Late Permian-Early Triassic, then this area would have been located in the northern part of the Gulf of Mexico. One may also mention that to assume tectonic continuity between Chiapas and the Yucatân peninsula may not be valid, since major discontinuities such as La Libertad arch (Fig. 5), the fault system of northern Chiapas, and the faults in northern Belice may represent effective tectonic boundaries (Viniegra, 1971). The earliest Cretaceous pole from the San Ricardo red beds (entry 37, Fig. 3) agrees well with the corresponding segment of the North American APWP thus suggesting that the 'Chiapas' block was keeping a similar relative position with respect to cratonic North America by that time.

Alternative explanations for observed discordances in the palaeomagnetic record may include the following:

1) Geomagnetic effects. Insufficient sampling to average out secular variation effects, or sampling of periodic excursions or polarity transitions which carried the geomagnetic pole away from the 'usual' position (this has been favored mainly by earlier workers, e.g. Guerrero-García, 1976). It may also include far-sided dipole field or non-dipole field behavior.

2) Undetected secondary magnetizations. This may affect to a certain degree some of the results, in particular, Cretaceous poles 11 and 7, Jurassic poles 13 and 14, and Permian pole 39, which are displaced from the corresponding segment of the reference path clearly away towards a younger segment of the path (Fig. 3). Partial overprints may affect some of the other entries, which sometimes show elongated site VGP distributions (e.g. Lower Tertiary pole 4).

3) Inadequate structural corrections. This may include unrecognized tilting, local thrusting, local rotation about an inclined axis (see MacDonald, 1980; Beck, 1980; and Symons, 1977; see discussion above of Triassic results from northeastern Mexico and Fig. 4).

4) Improper age assignments for rock units (also for remanence acquisition). The age of some rock units is not well constrained (e.g. pole 7 may range from 100 to 45 m.y.).

5) Anomalous remanence acquisition. It may include magnetic anisotropy effects, self-reversal effects and inclination error in sediments.

6) Experimental errors. Orientation or calculation errors, for example.

At present it is difficult to fully evaluate these possible explanations, and either one or a combination of them may account for some of the observations.

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