GEOFISICA

INTERNACIONAL

REVISTA DE LA UNION GEOFISICA MEXICANA, AUSPICIADA POR EL INSTITUTO DE GEOFISICA DE LA UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Vol. 27 México, D. F., 1o. de octubre de 1988 Núm. 4

MIOCENE PALEOMAGNETISM OF BAJA CALIFORNIA SUR; EVIDENCE CONCERNING THE STRUCTURAL DEVELOPMENT OF WESTERN MEXICO

B. P. HAUSBACK*

(Received: October 21, 1987)
(Accepted: March 15, 1988)

RESUMEN

Se ha determinado un polo paleomagnético, aparentemente del Mioceno inferior al medio, a 85.4°N, 71.2°E ($\alpha_{95} = 6.2°$) mediante mediciones del magnetismo remanente en rocas volcánicas en 16 sitios de Baja California Sur. Este polo no es significativamente diferente del polo paleomagnético de referencia, del Terciario medio, para el craton Norteamericano; por consiguiente, probablemente desde el Mioceno no ha ocurrido ningún movimiento latitudinal hacia el norte, de la Baja California con relación al interior de Norteamérica, mayor que el de 2° que indican las anomalías magnéticas en la boca del Golfo de California. Estudios paleomagnéticos previos han demostrado que hay rocas del Mioceno o más antiguas, de la porción continental de México, que presentan una rotación significativa en sentido "contra-reloj", con respecto a las direcciones paleomagnéticas del Mioceno tanto de Baja California como de la parte cratónica de Norteamérica. Parece probable que el corrimiento "contra-reloj" de la tierra firme de México ocurrió después de la iniciación de la ruptura, hace 12 m.a., del Golfo de California y que no afectó a la península de Baja California. El desgarramiento lateral derecho a lo largo de la península, asociado a la evolución del Golfo, puede haber causado una rotación localizada, del Plioceno al Reciente, en el sentido de las manecillas del reloj, de la Baja California Sur, con respecto a la porción continental de México.

* *Geology Department. California State University. 6000 J Street, Sacramento, California, 95819, U.S.A.*

ABSTRACT

An apparent lower to middle Miocene paleomagnetic pole at 85.4°N, 71.2°E ($\alpha_{95} = 6.2°$) has been determined from measurements of the remanent magnetization in volcanic rocks at 16 sites in Baja California Sur. This pole is not significantly different from the reference middle Tertiary paleomagnetic pole for the North American craton; hence, probably no more than the 2° latitudinal northward movement of Baja California relative to interior North America has occurred since the Miocene, as indicated by magnetic anomalies in the mouth of the Gulf of California. Previous paleomagnetic studies have shown that Miocene and older rocks from mainland Mexico display a significant counterclockwise rotation with respect to Miocene paleomagnetic directions from both Baja California and cratonic North America. It is likely that the mainland Mexican counterclockwise shift occurred after the 12 m.y. initiation of Gulf of California rifting and did not affect the Baja California peninsula. Right-lateral shear along the peninsula associated with Gulf development may have caused localized Pliocene to Recent clockwise rotation in Baja California Sur with respect to mainland Mexico.

INTRODUCTION

The Baja California peninsula has long been thought to be a rifted portion of western Mexico. Wegener (1929) based this conclusion on the geometrical fit of the peninsula into the indented coastline of the Mexican mainland and on the similarity of granitic rocks at the tip of the peninsula to those near Puerto Vallarta.

Recent studies have suggested that over 70% of the North American Cordillera is made up of exotic terranes that have been tectonically transported northward, primarily during the Mesozoic, but also in part during the Cenozoic (Beck *et al.*, 1980). Paleomagnetism is the most widely used tool for the measurement of these northerly movements. Parts of Baja California are likely to be exotic to North America (Coney *et al.*, 1980), yet, very few paleomagnetic data are available from the peninsula. Important paleomagnetic studies of Cretaceous rocks (Hagstrum *et al.*, 1985, 1986) and Neogene rocks (Pischke, 1979; Pischke *et al.*, 1979, 1986) have evaluated Baja California paleomagnetism. This paper expands upon Miocene paleomagnetic data previously summarized by Hausback (1984b, 1985) and Hagstrum *et al.* (1987).

Pischke (1979) and Pischke *et al.* (1979) studied Neogene volcanic rocks from Baja California Sur and concluded that the peninsula was 10° south of its present position in late Miocene time, alongside Central America. However, geological studies (Gastil *et al.*, 1973, 1976, 1979; and Hausback, 1984a) have correlated sedimentary, intrusive, and volcanic units across the Gulf of California, suggesting that the peninsula was a portion of western Mexico during the early Miocene and possibly has not moved much since late Cretaceous. Using marine magnetic anomalies in the mouth of the Gulf of California, Larson (1972) demonstrated that Baja California lay to the west of mainland Mexico during the Miocene and has shifted northward only 2° in the last 4 m.y. (million years) – considerably less than Pischke's estimate of 10° northerly movement.

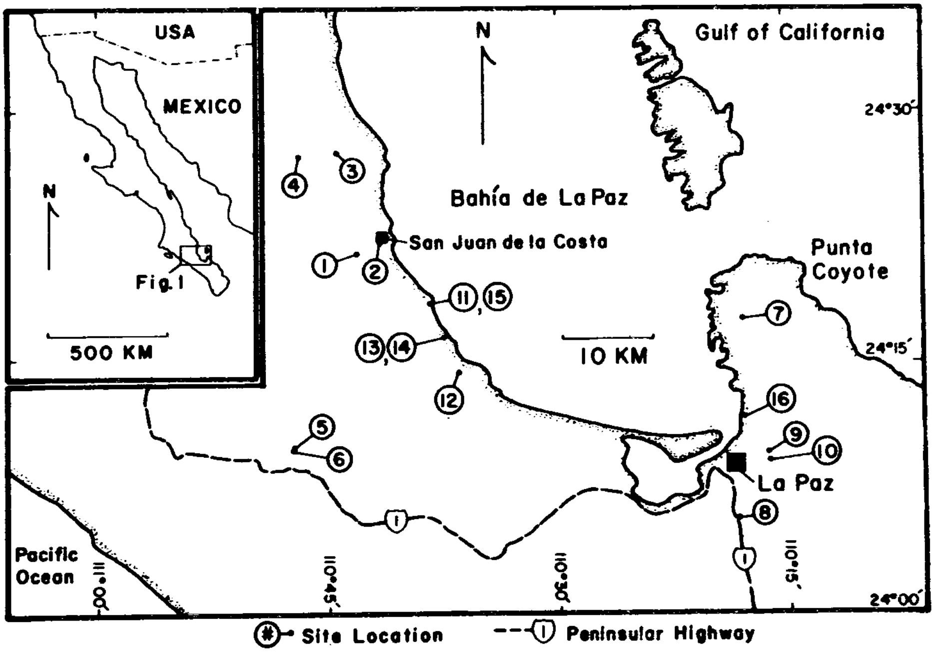

Fig. 1. Site location map.

The purpose of this study was to evaluate the magnitude of Neogene motion of the Baja peninsula with respect to the North American craton and mainland Mexico by a paleomagnetic investigation of early to middle Miocene rocks surrounding the Bahía de la Paz (Bay of La Paz) region of Baja California Sur. Here, the great escarpments facing the Gulf of California contain continuous exposures of nearly flat-lying Oligocene to middle Miocene volcanic, volcaniclastic, and sedimentary strata. Hausback (1984a) detailed the K-Ar geochronology of the Miocene Comondú and Isidro Formations which comprise the major portion of this sequence (Fig. 2). These two formations were sampled at sixteen different sites (Fig. 1) for paleomagnetic investigation. The Comondú and Isidro Formations are the products of a calc-alkaline continental volcanic arc that was active along what is now the axis of the Gulf of California during the early to middle Miocene.

PALEOMAGNETIC SAMPLES

At each of sixteen sampling sites located in the Bahía de La Paz region, 3 to 10 one inch-diameter oriented samples were taken using a gasoline powered diamond drill. Samples at thirteen of the sites are from individual ash-flow tuffs and lava flows, and the remainder are from short sections of volcaniclastic sandstone. The stratigraphic

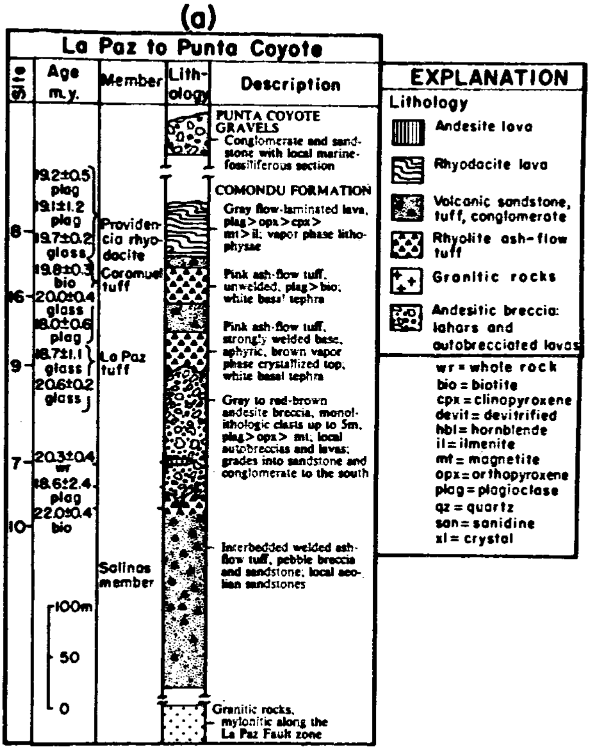

Fig. 2(a). Generalized stratigraphic columns in the La Paz area, showing stratigraphic positions of paleomagnetic sampling sites.

relationships are shown in Figure 2. All of the paleomagnetic sites but one are from deposits of different volcanic eruptions or sedimentary depositional periods. The exception is the La Paz tuff which was sampled in both the La Paz and San Juan de la Costa areas (sites 9 and 12).

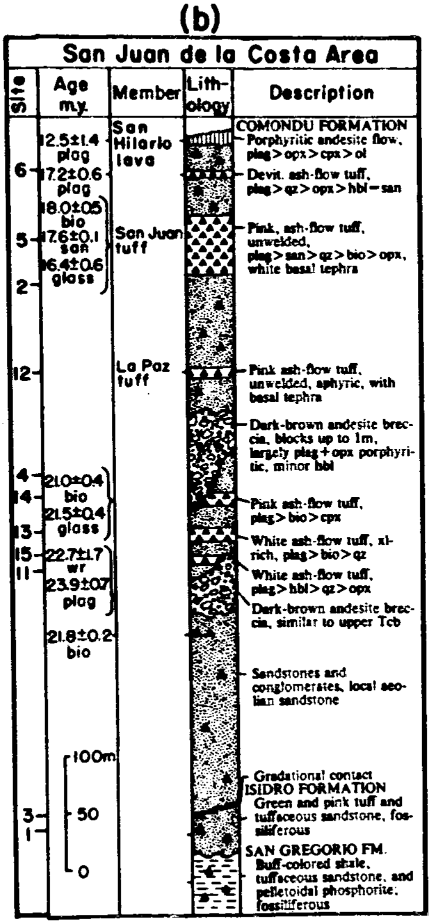

Fig. 2(b). Generalized stratigraphic columns in the San Juan de la Costa area, showing stratigraphic positions of paleomagnetic sampling sites.

Polished grain mounts of heavy mineral separates from the ash-flow tuffs consistently reveal one to two percent magnetite with exsolution lamellae of ilmenite. Commonly, magnetite grains are slightly oxidized with a light surficial coating of hematite, probably formed during recent weathering. Ilmenite is also present in most of the rocks as a small fraction of the ferro-magnesian phenocrysts.

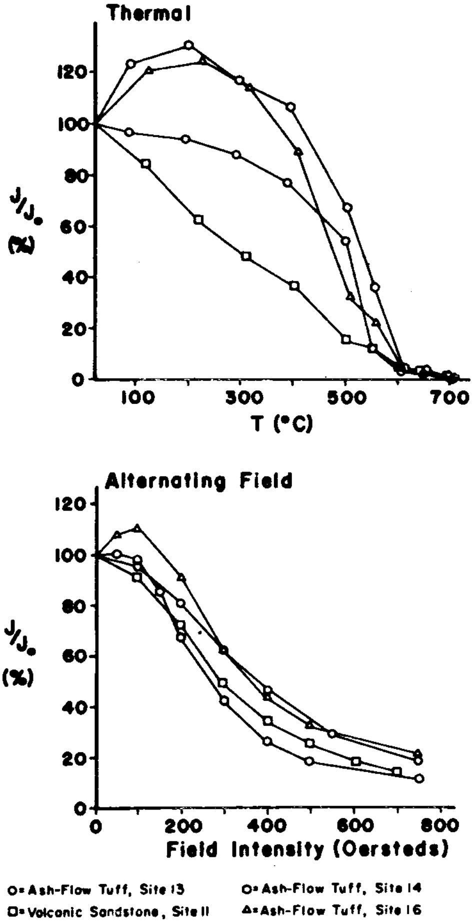

Fig. 3. Typical normalized thermal and AF demagnetization sequences, remanence intensity (J) normalized to the NRM intensity (J_0) versus demagnetization treatment.

MAGNETIC MEASUREMENTS

Magnetization of cylindrical 2.5 x 2.2 cm specimens cut from the core samples was measured using a cryogenic magnetometer at the Stanford University Paleomagnetic Laboratory. Natural remanent magnetization (NRM) intensities were found to be approximately 10^{-4} emu/cm^3 for the rhyolitic ash-flow tuffs and volcanic sandstones and 10^{-3} emu/cm^3 for andesitic lavas and lahars. Alternating field (AF) demagnetization was employed in a step-wise removal of spurious, low coercive-force magnetic overprints, presumably acquired from the recent geomagnetic field and from sample transportation and preparation. Thermal demagnetization was generally performed on one specimen per site, and 13 out of 15 sites yielded identical magnetization directions with both AF and thermal demagnetization. The presence of magnetite as the principal magnetic carrier is substantiated by the NRM intensity changes during thermal demagnetization (Fig. 3). The demagnetization curves for the ash-flow

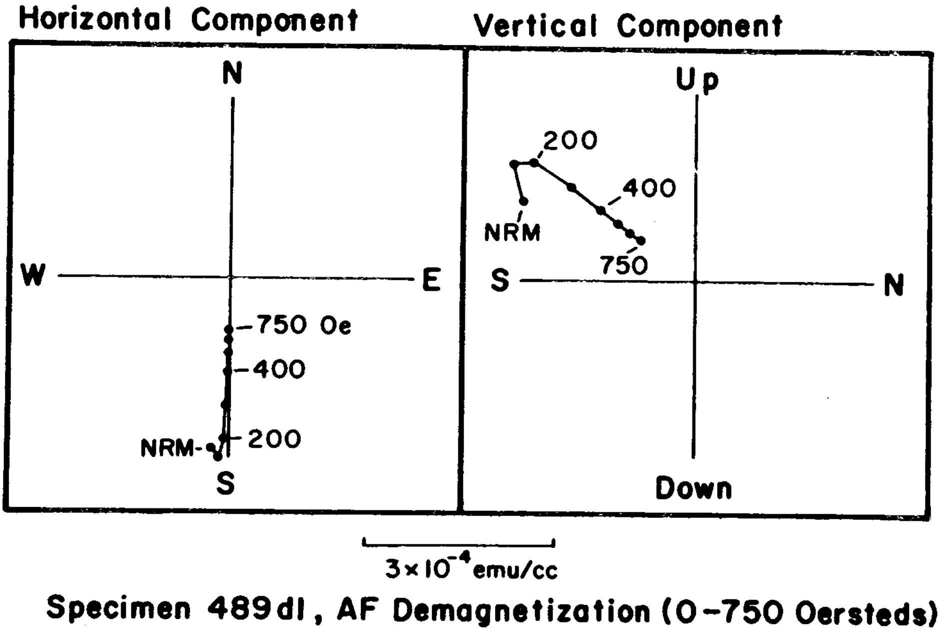

Fig. 4. Orthogonal vector diagram for a typical AF demagnetization sequence from an ash-flow tuff.

tuffs undergo their major collapse in intensity just below 600°C, close to the Curie temperature for magnetite (Tc = 578°C). A typical example of directional change during progressive demagnetization is illustrated by the orthogonal vector plot of Figure 4. The demagnetization procedure yielded a stable magnetization direction for each measured specimen. All stable samples carried a relatively highly coercive magnetic remanence, typically overprinted with a less coercive component. This stable, high coercive force magnetization is the component that did not change in direction as its intensity slowly decayed during successively higher demagnetization steps.

Table 1

Bahía de La Paz paleomagnetic data

Site	Rock type	Age (m.y.)	N	Magnetization directions				Virtual geomagnetic N pole	
				Inc.	Dec.	k	α_{95}	Lat.(N)	Long.(E)
San Juan de la Costa area (in stratigraphic order)									
6	Ash-flow tuff	17.2*	7	46.7	355.3	399	2.6	84.3	202.1
5	Ash-flow tuff	17.6*	8	33.7	4.2	488	2.2	83.1	34.0
2	Volc sandstone	~18	5	26.7	11.8	157	5.0	74.9	19.8
12†	Ash-flow tuff	20*	7	−37.9	180.4	623	2.1	− 87.0	242.6
4	Ash-flow tuff	~21	5	−33.3	169.0	169	4.8	− 78.0	309.8
14	Ash-flow tuff	21.0*	6	−38.9	140.6	285	3.4	− 53.8	343.9
13	Ash-flow tuff	~22	7	13.5	345.3	133	4.6	67.6	110.9
15	Ash-flow tuff	~22	7	20.7	12.8	857	1.8	71.8	25.4
11	Volc. sandstone	~22	5	45.0	359.3	57	8.3	87.6	233.9
3	Volc. sandstone^{+} Water-lain tuff	~24	5	26.6	326.9	28	11.7	57.2	146.9
1	Volc. sandstone^{+} Water-lain tuff	~24	5	57.2	10.8	12	18.3	73.7	281.0

All data are corrected for the local dip of bedding.
Ages after Hausback (1984a).
N = number of samples in calculation.
Inc., Dec. = inclination and declination (+ = down).

k = precision parameter (Fisher, 1953).
α_{95} = radius, in degrees, of 95% cone of confidence.
* = K-Ar date directly from the sampled unit.
† = Sites 9 and 12 are averaged before regional mean pole calculations.
(1) = calculated from average magnetized directions.

Table 1 (Cont.)

Site	Rock type	Age (m.y.)	N	Magnetization directions			α_{95}	Virtual geomagnetic N pole	
				Inc.	Dec.	k		Lat.(N)	Long.(E)
La Paz area (in stratigraphic order)									
8	Rhyodacite lava	19*	8	36.3	342.8	114	4.6	73.6	149.2
16	Ash-flow tuff	19.8*	6	−33.2	186.5	399	2.9	−81.4	203.7
9†	Ash-flow tuff	20*	10	−35.7	183.5	447	2.1	−84.5	212.6
7	Andesite lava⁺ autobreccia	~20	7	22.5	27.1	5	23.8	61.4	1.0
10	Ash-flow tuff	23.2*	3	−32.2	173.4	388	4.1	80.9	113.4
Area averages								Paleomagnetic N pole(1)	
La Paz area, mean of sites			5	33.0	3.0	29	11.7	83.2	45.2
San Juan de la Costa area, mean of sites			11	35.8	354.2	18	9.9	83.0	120.4
Mean of all normal sites			10	34.2	359.7	16	11.0	84.5	72.7
Mean of all reversed sites			6	−36.0	173.2	35	9.6	−82.4	306.8
Mean for Bahía de La Paz region† (this study)			15	34.8	356.8	20	8.9	83.9	98.4
Mean for Baja California Sur (Miocene) (Combination of this study + Pischke, 1979, from Table 2)			30	35.9	359.8	19	6.2	85.4	71.2

INTERPRETATION OF PALEOMAGNETIC RESULTS

Site mean directions are listed in Table 1 and illustrated in Figure 5. Each site probably represents a single moment in time (for the volcanic sites) or a limited time period (for the sedimentary sites), as reflected by the generally large precision parameters (k) in Table 1.

Two observations suggest that the magnetization are primary, acquired at the time of cooling or deposition of the volcanic or sedimentary units.

1) A positive conglomerate test.

Directions of magnetization from cobble-sized clasts in fluvial conglomerate are randomly distributed, implying that the magnetization of these cobbles has not been overprinted since the cobbles were deposited.

2) Consistent normal and reversed directions.

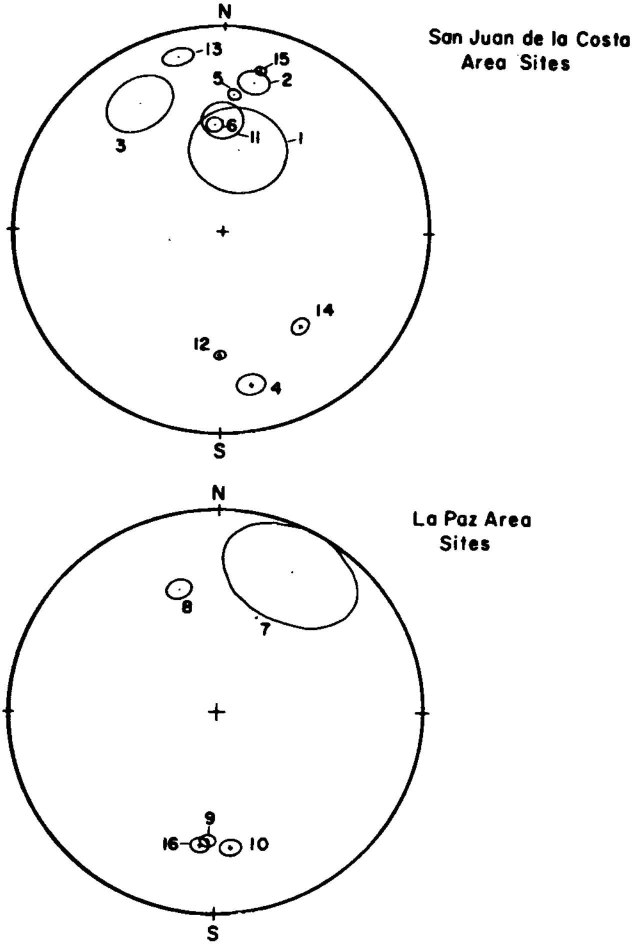

Fig. 5. Site mean magnetic vector orientations, with α_{95} confidence limits. Equal-area, lower hemisphere stereonet projection. Reversed sites are plotted in the upper hemisphere and are indicated with a cross at their centers.

The site mean directions cluster in two antipodal groups. These magnetizations were acquired during normal and reverse geomagnetic epochs. Their antipodal distribution suggests that they have not been overprinted. The averaged magnetization directions for the collective normal and reversed sites are given in Table 1.

Stable characteristic magnetizations probably represent the thermo-remanent magnetization (TRM) of the ash-flow tuffs and lava flows and the post-depositional detrital-remanent magnetization (DRM) in the sandstones.

In order to evaluate local tectonic rotations, the paleomagnetic results are divided into two geographic groups, one containing the sites surrounding San Juan de la Cos-

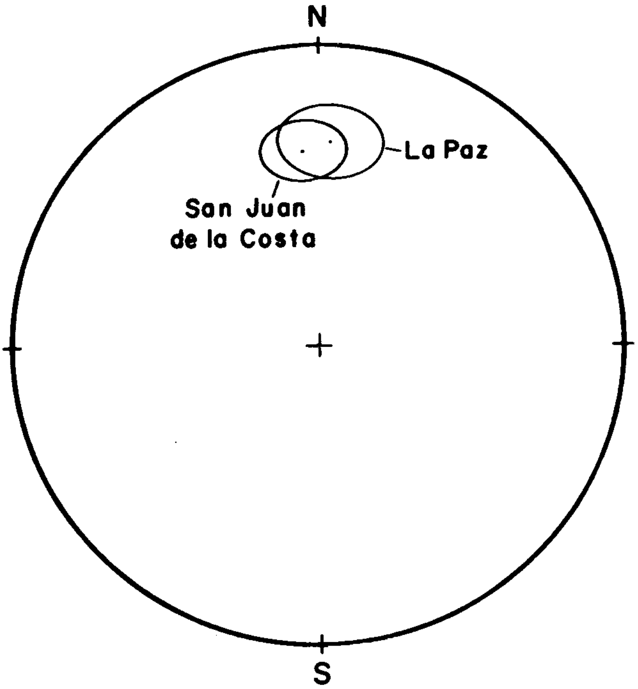

Fig. 6. Average magnetic vector orientations of sites from La Paz and San Juan de la Costa areas, with α_{95} confidence limits. Equal-area, lower hemisphere stereonet projection.

ta and the other containing the sites around La Paz. The site mean directions have been averaged in order to remove the effect of geomagnetic secular variation (Fig. 6). The averaged directions for the two areas show no significant relative rotation relative to each other at the 95% or 63% confidence level (α_{95} and α_{63} circles overlap). Furthermore, the La Paz tuff has been correlated between the two areas (Hausback, 1984a) and the mean orientations of both sites are not significantly different, even with small α_{95} radii of 2° (site 9 compared with site 12). Since sites 9 and 12 are from the same unit, they have been averaged before inclusion in the mean pole calculation in Table 1.

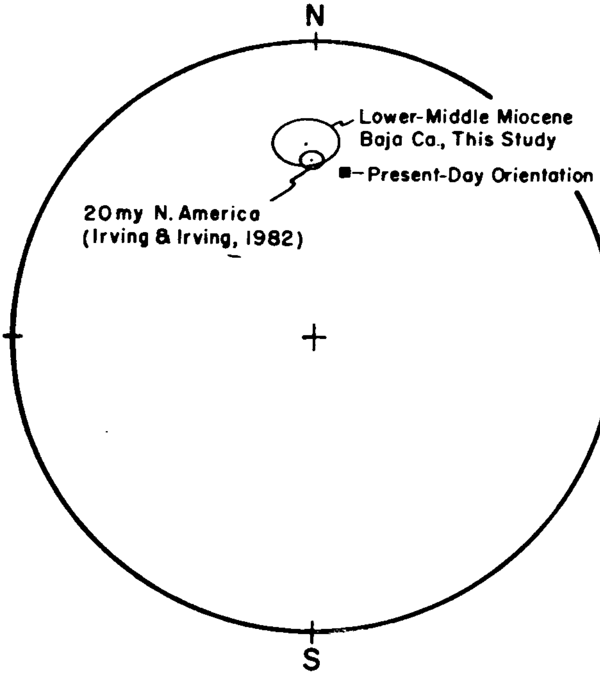

Fig. 7. Bahía de La Paz regional average paleomagnetic direction shown with Irving and Irving's (1982) estimate of the expected orientations developed from 20 m.y. old cratonic North American paleomagnetic poles, with α_{95} confidence limits. Present-day orientation of the Earth's magnetic field is also shown. Equal-area, lower hemisphere stereonet projection.

Since relative movement can be ruled out, all 15 sites in the Bahía de La Paz region can be averaged (Fig. 7). This early to middle Miocene magnetization direction for Baja California Sur does not differ significantly at the 95% and 63% confidence levels from the expected direction of the Earth's magnetic field in Baja California Sur derived from the averaged paleomagnetic pole position for middle to upper Tertiary rocks of cratonic North America (Irving and Irving, 1982; Irving, 1979; McElhinny, 1973). The mean pole for Baja California Sur is statistically different from the present-day orientation of the Earth's magnetic field, demonstrating that these rocks have not been magnetically overprinted by post 15 m.y. processes.

CONCLUSIONS AND DISCUSSION

Pischke (1979) based his estimate of a 10° latitudinal post-Miocene northward shift of Baja California upon data which did not average secular variation. In his analysis, Pischke showed that the majority of his 21 sites (Table 2) indicate a paleolatitude to the south of their present latitude. However, 4 of the sites also show paleolatitudes substantially to the north of their present latitude. Pischke's site data have been reevaluated here; the mean magnetic vector orientation is shown in Fig. 8a. Six of Pischke's original sites were excluded from the calculation of the mean paleomagnetic orientation. Five of these sites (IM1 to IM5) indicate localized clockwise rotation of the San Ignacio area (Pischke, 1979; Sawlan and Smith, 1983). The sixth of the excluded sites (LM1) yielded a low Koenigsberger ratio (0.5; Pischke, 1979) indicating that the rock does not carry a stable remanent magnetization (Pischke, 1979; Hagstrum *et al.*, 1987). There is no statistical difference between the mean paleomagnetic orientation derived from the data in this study and that calculated from Pischke's data. Combining the two data sets yields a best available determination of the Miocene magnetic field orientation in Baja California Sur (Fig. 8b).

Because of the approximately 2° uncertainty inherent in the averaging of secular variation of the geomagnetic field, paleomagnetic data cannot measure the small latitudinal shift of Baja California since the Miocene. The data show, however, that there has probably not been a large-scale (10°) northward translation of Baja California, as was reported by Pischke (1979). Larson's (1972) suggestion of a 2° northward latitudinal movement in the last 4 m.y. based on magnetic anomalies in the Gulf of California is in concordance with the paleomagnetic results from this study as well as a more extensive compilation of Miocene paleomagnetism for Baja California by Hagstrum *et al.* (1987).

Table 2

Baja California paleomagnetic data from Pischke (1979, p.32)

Site	Age	N	Magnetization directions				Virtual geomagnetic N pole	
	(m.y.)		Inc.	Dec.	k	α_{95}	Lat.(N)	Long.(E)
OM1	14.4*	7	−34	179	55	8.2	79.6	65
OM2	13	9	61	360	424	2.5	76.9	66
OM3	12.5*	8	65	358	228	3.7	71.9	70
AM1	8.1*	5	−35	185	320	4.3	81.0	34
AM2	13	6	−39	186	271	4.1	82.5	17
IM1†	10	6	28	45	926	2.2	46.5	344
IM2†	10.8*	5	26	46	2039	1.7	45.1	345
IM3†	11	6	17	41	113	6.3	47.0	355
IM4†	11	6	20	48	1166	2.0	41.8	348
IM5†	11	7	22	45	81	7.5	45.0	349
IM6	5	7	31	360	143	6.3	79.6	68
IM7	5.1*	5	35	358	238	5.0	81.7	79
IM8	5	6	30	358	447	3.2	78.8	76
JM1	11.0*	6	−18	176	63	8.5	72.9	82
JM2	14.3*	7	−15	218	47	8.9	49.5	358
JM3	18.7*	7	−39	207	162	4.8	65.1	341
JM4	19	6	−15	184	53	9.3	71.3	56
JM5	7.6*	6	57	3	202	4.7	78.0	57
LM1†		5	−86	23	61	9.9	16.9	246
LM2	9.0	7	−40	177	223	4.1	86.8	131
LM3	14.9*	6	28	336	38	11.0	65.6	142
Mean for Baja California from Pischke (1979) data								
		15	36.9	2.8	18	9.3	85.3	34.4

N = number of samples in calculation.
Inc., Dec. = inclination and declination, (+ = down).
k = precision parameter (Fisher, 1953)

α_{95} = radius, in degrees, of 95% cone of confidence.
* = K-Ar date directly from sampled unit.
† = sites excluded from mean pole calculation (see text).

TECTONIC RELATIONSHIPS BETWEEN BAJA AND MAINLAND MEXICO

The Baja California Miocene magnetization directions can be compared with those from similar-aged rocks found in mainland Mexico. Figure 9 shows available lower

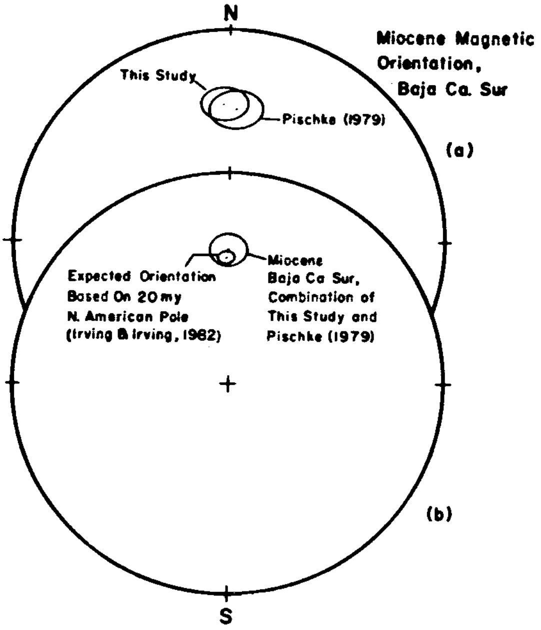

Fig. 8. Baja California Sur regional Miocene paleomagnetic directions. *(a)* From this study and from Pischke (1979), with α_{95} confidence limits. *(b)* Combined and averaged from the aforementioned two studies. Equal-area, lower hemisphere stereonet projection.

to middle Tertiary paleomagnetic poles for mainland Mexico and Baja California. It appears that mainland Mexico has undergone a counterclockwise rotation of 20° - 25° (locally more) with respect to cratonic North America (Urrutia-Fucugauchi and Pal, 1977; Urrutia-Fucugauchi, 1981a), probably after the middle Miocene. The rifting and northward shift of the Baja California peninsula was a major Neogene structural event, and therefore it is important to determine the relative chronology of this western rifting event and the counterclockwise rotational event of Mexico.

The Miocene paleomagnetic pole of Baja California Sur (Table 1) shows no significant rotation with respect to the cratonic North American middle Tertiary pole. However, Pischke (1979) and Sawlan and Smith (1983) have suggested that some Miocene rocks in Baja California have been locally rotated in a clockwise sense with respect to the averaged pole. In addition, paleomagnetic results from Pliocene muds in northern Baja California show a 30° clockwise rotation (Strangway *et al.*, 1971). However, these muds may have acquired a chemical remanent magnetization that has obscured the original magnetization directions (Larson and Walker, 1975). Unfortunately, without correlative Pliocene poles from mainland Mexico and early to middle Tertiary poles from Baja California, the comparison of the two regions is in-

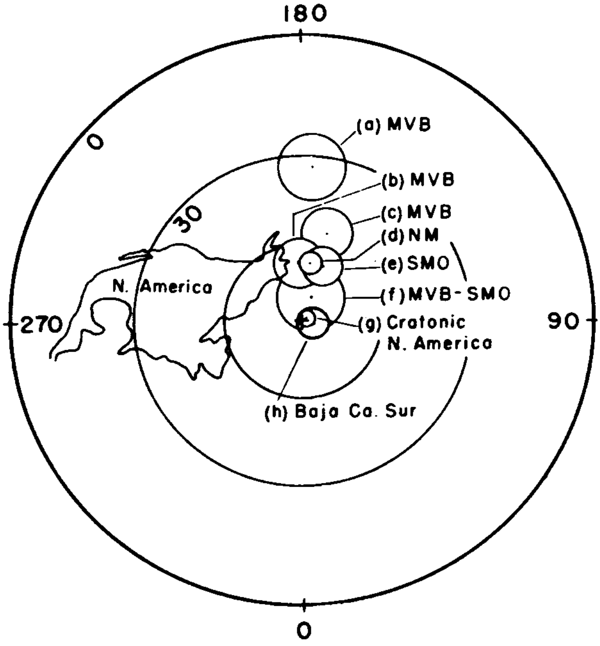

Fig. 9. Equal-angle polar projection of the Earth showing apparent paleomagnetic poles for Tertiary rocks from Baja California and mainland Mexico with α_{95} confidence limits. Abbreviations: MVB = Mexican Volcanic Belt; NM = northern mainland Mexico; SMO = Sierra Madre Occidental. Data from: *(a)* Miocene Jantetelco Granodiorites and Tepexco lavas, Urrutia-Fucugauchi, 1981b; *(b)* Oligocene volcanic rocks, Jalisco, Urrutia-Fucugauchi and Pal, 1977; *(c)* Oligocene-Miocene Guerrero volcanics, Urrutia-Fucugauchi and Böhnel, 1987; *(d)* Eocene volcanics, Chihuahua, Urrutia-Fucugauchi, 1981a; *(e)* Oligocene-Miocene volcanics, Durango-Mazatlán highway, Nairn *et al.* 1975; *(f)* Upper Miocene Santiago Volcanics, Watkins *et al.*, 1971; *(g)* 20 m.y. old paleomagnetic pole for cratonic North America, Irving and Irving, 1982; *(h)* Miocene, Baja California, data combined from this study and from Pischke, 1979.

complete, and the entire history of counterclockwise rotation of Mexico and its relationship to the spreading of the Gulf of California can only be partially evaluated.

It would appear that several of the widely observed counterclockwise rotations in Mexico have occurred along or near proposed east-west-trending, left-lateral shear structures distributed through Mexico (Urrutia-Fucugauchi, 1981a, b and Walper, 1980) as well as local oroclinal bending (Kleist *et al.* , 1984). Urrutia-Fucugauchi (1981a) suggests that the counterclockwise rotation of Mexico may be due in part to approximately 1000 km of post-Oligocene, left-lateral movement along the Texas lineament (Fig. 10). The observed rotated paleomagnetic directions from mainland Mexico may suggest that the entire subcontinent of Mexico has undergone counterclockwise rotation. This large scale rotation was most likely caused by movement along a series of major left-lateral structures (Walper, 1980) between the Texas lineament, bounding Mexico on the north, and the Motagua-Polochic fracture zone, bounding Mexico on the south. Activity along the Motagua-Polochic fracture zone began during the Eocene (Mattson, 1979) and present activity has been seismically documented (Molnar and Sykes, 1969). The eastward continuation of this structure in the Caribbean Sea has had a maximum displacement of 3000 km (Alvarez, 1982). The evaluation of counterclockwise rotations in Mexico and their relationship to these proposed structures is not attempted here, but an essential test of this model would be the actual delineation of the major left-lateral discontinuities and proof of the magnitude and timing of their displacement.

Pliocene to recent clockwise rotations along Baja California may have locally taken place along a series of northwest-trending, right-lateral, transpeninsular discontinuities delineated by Normark and Curray (1968) and Allen *et al.* (1960).

Two possible models are proposed here to explain the timing of probable rotations of mainland Mexico with respect to Baja California giving rise to the divergent paleomagnetic orientations:

1) No rotation of Mexico occurred until after the split of Baja California from the mainland (Fig. 10a). After (or during) initial separation beginning about 12 m.y. ago (Hausback, 1984a) and culminating in sea-floor spreading about 4 m.y. ago (Larson, 1972), the Mexican mainland rotated counterclockwise with respect to Baja California and the rest of the North American plate due to left-lateral shear along east-west-trending faults between and including the Texas lineament

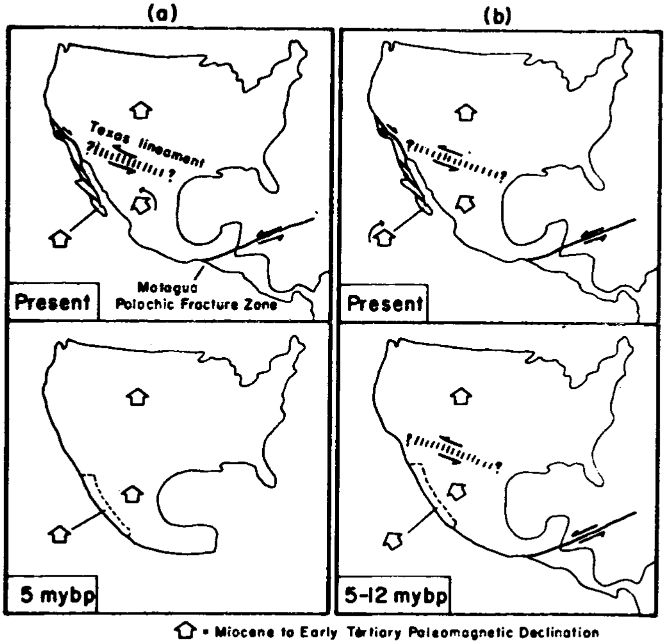

Fig. 10. Summary of 2 models proposed to explain the timing of divergent middle Tertiary paleomagnetic orientations between Baja California and mainland Mexico.

and the Motagua-Polochic fracture zone. Coincident right-lateral shear along the Baja peninsula associated with the Gulf rifting caused only local clockwise rotations.

2) Much of the counterclockwise rotation of Mexico, then including Baja California, began in the middle to late Miocene, *before* the 12 m.y. decoupling of Baja California from the mainland (Fig. 10b). In this less likely scenario, the Miocene and older units would have been rotated counterclockwise in a similar fashion to the first model in both mainland Mexico and what is now Baja California prior to the late Miocene. After 12 m.y. ago, right-lateral shear associated with the rifting of the Gulf of California may have reoriented the Baja poles, through clockwise rotation, (fortuitously) back to the cratonic North American direction.

ACKNOWLEDGEMENTS

The author is very grateful to Mike McWilliams for generously allowing the use of the cryogenic magnetometer at Stanford University, and to Lung Chan for supplying fine statistical computer programs for this study. The work would not have been possible without material and technical support from Len Vigus of the University of California, Consejo de Recursos Minerales, the U. S. Geological Survey, and Roca Fosfórica Mexicana. Many thanks are due the reviewers of this manuscript: J. Urrutia-Fucugauchi, Mike McWilliams, Clyde Wahrhafting, Bradley Erskine, Lung Chan, Mary Gilzean, Garniss Curtis, and Bill Houston.

BIBLIOGRAPHY

ALLEN, C. R., L. T. SILVER and F. G. STEHLE, 1960. Agua Blanca fault - a major transverse structure of northern Baja California, Mexico. *Geol. Soc. Am. Bull. 71,* 457-482.

ALVAREZ, W., 1982. Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics. *J. Geophys. Res., 87,* (B8), 6697-6710.

BECK, M., A. COX and D. L. JONES, 1980. Mesozoic and Cenozoic microplate tectonics of western North America. *Geology, 8* (9), 454-456.

CONEY, P. J., D. L. JONES and J. W. H. MONGER, 1980. Cordilleran suspect terranes. *Nature, 288,* 329-333.

FISHER, R. A., 1953. Dispersion on a sphere. *Proc. Roy. Soc. Lond., Series a, 217,* 295-305.

GASTIL, G., D. KRUMMENACHER and J. MINCH, 1979. The record of Cenozoic volcanism around the Gulf of California. *Geol. Soc. Am. Bull., 90,* 839-857.

GASTIL, G., D. KRUMMENACHER, J. DOUPONT, J. BUSHEE, W. JENSKY and D. BARTHELMY, 1976. La zona batolítica del sur de California y el occidente de México. *Soc. Geol. Mex., Bol., 37,* 84-90.

GASTIL, G., D. LEMONE and W. STEWART, 1973. Permian fusulinids from near San Felipe, Baja California. *Am. Ass. Petrol. Geol., Bull., 57,* 746-747.

HAGSTRUM, J. T., M. G. SAWLAN, B. P. HAUSBACK, J. G. SMITH and C. S. GROMME, 1987. Miocene paleomagnetism and tectonic setting of the Baja California peninsula, Mexico. *J. Geophys. Res., 92,* (B3), 2627-2639.

HAGSTRUM, J. T., M. McWILLIAMS, D. G. HOWELL and S. GROMME, 1986. Mesozoic paleomagnetism and northward translation of the Baja California peninsula: Reply. *Geol. Soc. Am., Bull., 97,* 1280.

HAGSTRUM, J. T., M. McWILLIAMS, D. G. HOWELL and S. GROMME, 1985. Mesozoic paleomagnetism and northward translation of the Baja California peninsula. *Geol. Soc. Am. Bull., 96,* 1077-1090.

HAUSBACK, B. P., 1984a. Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico. *In:* V. A. Frizzell, Jr. (Ed.), Geology of the Baja California peninsula: Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, California. *39,* 219-236.

HAUSBACK, B. P., 1984b. Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico (Ph. D. Thesis). University of California, Berkeley, 162 pp.

HAUSBACK, B. O., 1985. Miocene paleomagnetism of Baja California Sur - evidence concerning the structural development of western Mexico. *Geol. Soc. Am.*, Cordilleran Section, Abstracts with programs, *17* (6), p. 360.

IRVING, E., 1979. Paleopoles and paleolatitudes of North America and speculations about displaced terrains. *Can. J. Earth Sci., 16,* 669-694.

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

KLEIST, R., S. A. HALL and I. EVANS, 1984. A paleomagnetic study of the lower Cretaceous Cupido Limestone, northeast Mexico: evidence for local rotation within the Sierra Madre Oriental. *Geol. Soc. Am. Bull., 95,* 55-60.

LARSON, E. E., and T. R. WALKER, 1975. Development of chemical remanent magnetization during early stages of red-bed formation in Late Cenozoic sediments, Baja California. *Geol. Soc. Am. Bull., 86,* 639-650.

LARSON, R. L., 1972. Bathymetry, magnetic anomalies, and plate tectonic history of the mouth of the Gulf of California. *Geol. Soc. Am. Bull., 83,* 3345-3359.

MATTSON, P. H., 1979. Subduction, buoyant braking, flipping, and strike-slip faulting in the northern Caribbean. *J. Geol., 87,* 293-304.

McELHINNY, M. W., 1973. Paleomagnetism and Plate Tectonics. Cambridge University Press, Cambridge, 358 pp.

MOLNAR, P. and SYKES, L. R., 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. *Geol. Soc. Am., Bull., 80,* 1639-1684.

NAIRN, A. E. M., J. F. W. NEGENDANK, H. C. NOLTIMIER and T. J. SCHMITT, 1975. Paleomagnetic investigations of the Tertiary and Quaternary rocks, X: The ignimbrites and lava units west of Durango, Mexico. *Neues Jahrbuch für Geol. und Paläont, Monatshefte,* 664-678.

NORMARK, W. R. and J. R. CURRAY, 1968. Geology and structure of the tip of Baja California, Mexico. *Geol. Soc. Am. Bull., 79,* 1589-1600.

PISCHKE, G., G. GASTIL and M. MARSHALL, 1986. Mesozoic paleomagnetism and northward translation of the Baja California Peninsula: Discussion. *Geol. Soc. Am., Bull., 97,* 1279.

PISCHKE, G. M., C. M. MARSHALL and R. G. GASTIL, 1979. Miocene paleomagnetic study of the tectonic history of Baja California, Mexico. *Geol. Soc. Am.,* Abstracts with Programs, *11* (3), 122.

PISCHKE, G. M., 1979. Paleomagnetic study of the Neogene tectonic history of Baja California, Mexico (M. S. thesis). San Diego State University, California, 97 pp.

SAWLAN, M. G. and J. G. SMITH, 1983. Discordant directions of Neogene lavas in Baja California Sur, Mexico: tectonics or field variations? (abstract). *EOS, Trans. Am. Geophys. Union, 64* (45), p. 686.

STRANGWAY, D. W., B. E. McMAHONE, T. R. WALKER and E. E. LARSON, 1971. Anomalous Pliocene paleomagnetic pole positions from Baja California. *Earth Planet. Sci. Lett., 13,* 161-166.

URRUTIA-FUCUGAUCHI, J., 1981a. Paleomagnetic evidence for tectonic rotation of northern Mexico and the continuity of the Cordilleran orogenic belt between Nevada and Chihuahua. *Geology, 9* (4), 178-183.

URRUTIA-FUCUGAUCHI, J., 1981b. Paleomagnetism of the Miocene Jantetelco granodiorites and Tepexco volcanic group and inferences for crustal block rotation in central Mexico. *Tectonophysics, 76,* 149-168.

URRUTIA-FUCUGAUCHI, J. and H. BÖHNEL, 1987. Tectonic interpretation of the Trans-Mexican Volcanic Belt - Discussion. *Tectonophysics, 138,* 319-323.

URRUTIA-FUCUGAUCHI, J. and S. PAL, 1977. Paleomagnetic data from Tertiary igneous rocks northeast Jalisco, Mexico. *Earth Planet. Sci. Lett., 36,* 202-206.

WALPER, J. L., 1980. Tectonic evolution of the Gulf of Mexico. *In:* R. H. Pilger, Jr. (Ed.). The origin of the Gulf of Mexico and the early opening of the central North Atlantic Ocean. Symposium, Louisiana State University, Proc., 87-98.

WATKINS, N. D., B. M. GUNN, A. K. BAKSI and J. ADE-HALL, 1971. Paleomagnetism, geochemistry and potassium-argon ages of the Rio Grande de Santiago volcanics, central Mexico. *Geol. Soc. Am. Bull., 82,* 1955-1968.

WEGENER, A., 1929. The Origin of Continents and Oceans. Dutton, N. Y., fourth edition (first edition, 1915), 212 pp.