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Gose, W. A., A. Perarnau, and J. Castillo, 2003, Paleomagnetic results from the Perijá Mountains, Venezuela: An example of vertical axis rotation, *in* C. Bartolini, R. T. Buffler, and J. Blickwede, eds., The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics: AAPG Memoir 79, p. 969–975.

Paleomagnetic Results from the Perijá Mountains, Venezuela: An Example of Vertical Axis Rotation

Wulf A. Gose

Department of Geological Sciences, The University of Texas at Austin, Austin, Texas, U.S.A.

Adrián Perarnau[1]

Departamento de Física, Universidad Simón Bolívar, Caracas, Venezuela

Jesús Castillo

Departamento de Física, Universidad Simón Bolívar, Caracas, Venezuela

ABSTRACT

Paleomagnetic analyses of 161 samples of Jurassic through Eocene age from 11 sites in the Venezuelan foothills of the Perijá Mountains yield a pole position at 44.1° N, 6.6° E with an error of A_{95} = 9.6°. These data indicate that the sampling sites underwent a 50° ± 12° clockwise rotation. The rotations are interpreted to be the result of Neogene compression, which caused the rotation of fault-bounded blocks. Model calculations suggest a shortening between 8 km and 20 km across the eastern portion of the Perijá Mountains.

INTRODUCTION

The Maracaibo Basin of Venezuela is bounded in the east by the Mérida Andes and in the west by the Santander Massif and the Perijá Mountains (Figure 1). Paleomagnetic data from Mesozoic strata from the Mérida Andes yielded a pole position that is in agreement with other poles from stable South America, which confirm the geological argument that the Mérida Andes are anchored to the Guayana Shield by the Precambrian Mérida Arch (Castillo et al., 1991; Zambrano et al., 1972). Maze (1983) and Maze and Hargraves (1984) reported paleomagnetic results from the Jurassic La Quinta Formation in the Perijá Mountains that they interpret to indicate a 50° counterclockwise rotation of the range. However, these data are statistically not acceptable. Of the 12 sampling sites in the La Quinta Formation, only 6 have a circle of 95% confidence (α_{95}) of less than 30°, a rather generously large error limit. The mean of these sites has a declination of 355°, an inclination of 34°, and an α_{95} = 64°. Clearly, no meaningful conclusions can be drawn from such data.

In a joint program between the University of Texas at Austin and the Universidad Simón Bolívar in Caracas we collected Mesozoic and Tertiary strata in the Perijá Mountains to complement our sampling

[1]*Current affiliation*: Baker Atlas, Maturin, Venezuela.

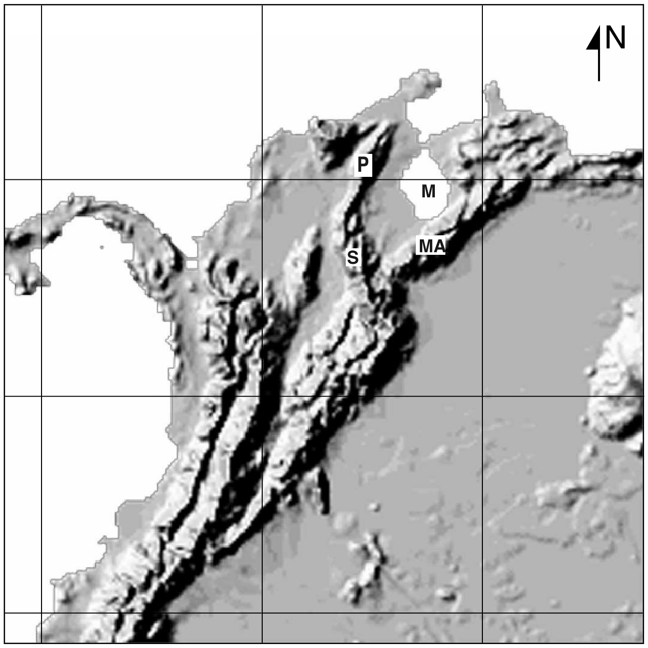


Figure 1. Map of northwestern South America (U.S. Geological Survey EROS Data Center). M = Lake Maracaibo; MA = Mérida Andes; P = Perijá Mountains; S = Santander Massif.

in the Mérida Andes. Initial results of this work were presented by Gose et al. (1993).

PALEOMAGNETIC RESULTS

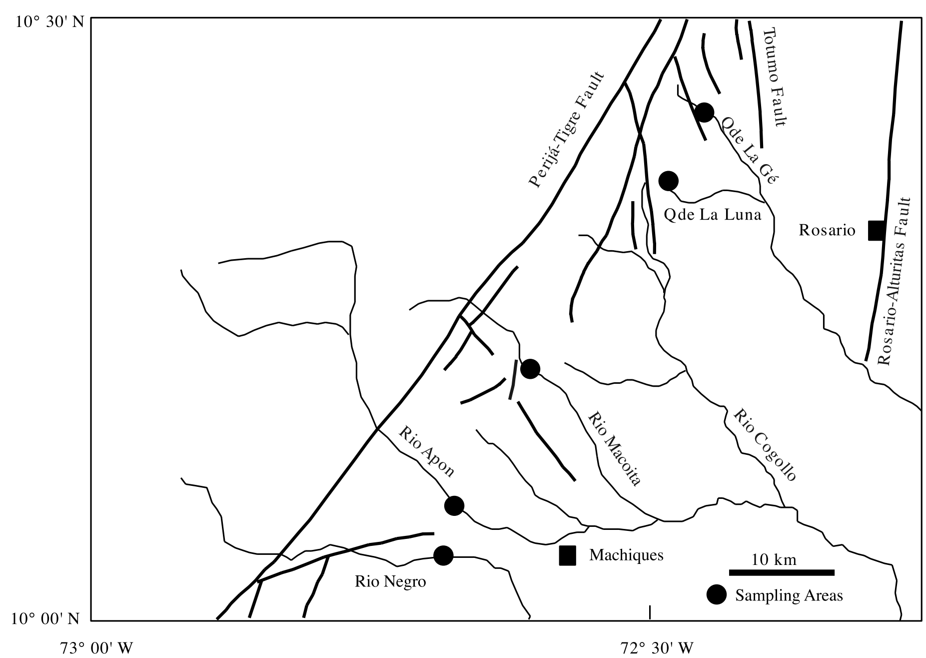
At 11 locations in the Venezuelan foothills of the Perijá Mountains (Figure 2), we collected 161 paleomagnetic samples by means of a portable drill. Half the samples were measured at the Universidad Simón Bolívar and half at the University of Texas. All samples were subjected to progressive demagnetization, and the results were evaluated using vector component diagrams (Figure 3). Most samples exhibited reasonably well-defined trends so that the characteristic directions of magnetization could be calculated by principal component analysis (Kirschvink, 1980). The mean directions and the statistical parameters are listed in Table 1.

The Jurassic/Cretaceous red beds of the La Quinta Formation were sampled in two areas along Rio Macoita, where the strata were dipping between 30 and 50° in a southeasterly direction. Most samples revealed their characteristic direction of magnetization in the temperature range of 500 to 675°C (Figure 3). The directions before and after correcting for the bedding attitudes are shown in Figure 4. The structural correction is sufficiently variable that the fold test could be applied. The directions cluster better at the 99% significance level after correcting for the bedding tilt, establishing that the magnetization is pre-folding.

The limestones of the lower Cretaceous Cogollo Group were collected along Quebrada La Gé and Rio Apón. These rocks are very weakly magnetized with initial intensities of 3 to 10 × 10^{-5} A/m. They could be thermally demagnetized only to 350°C, or sometimes even less, before their intensities fell below the noise level of the magnetometer.

The La Luna Formation was sampled at four locations along Quebrada La Luna. Two reversely

Figure 2. Location of sampling areas. The map is based on the geological map of Venezuela (Bellizzia et al., 1976).



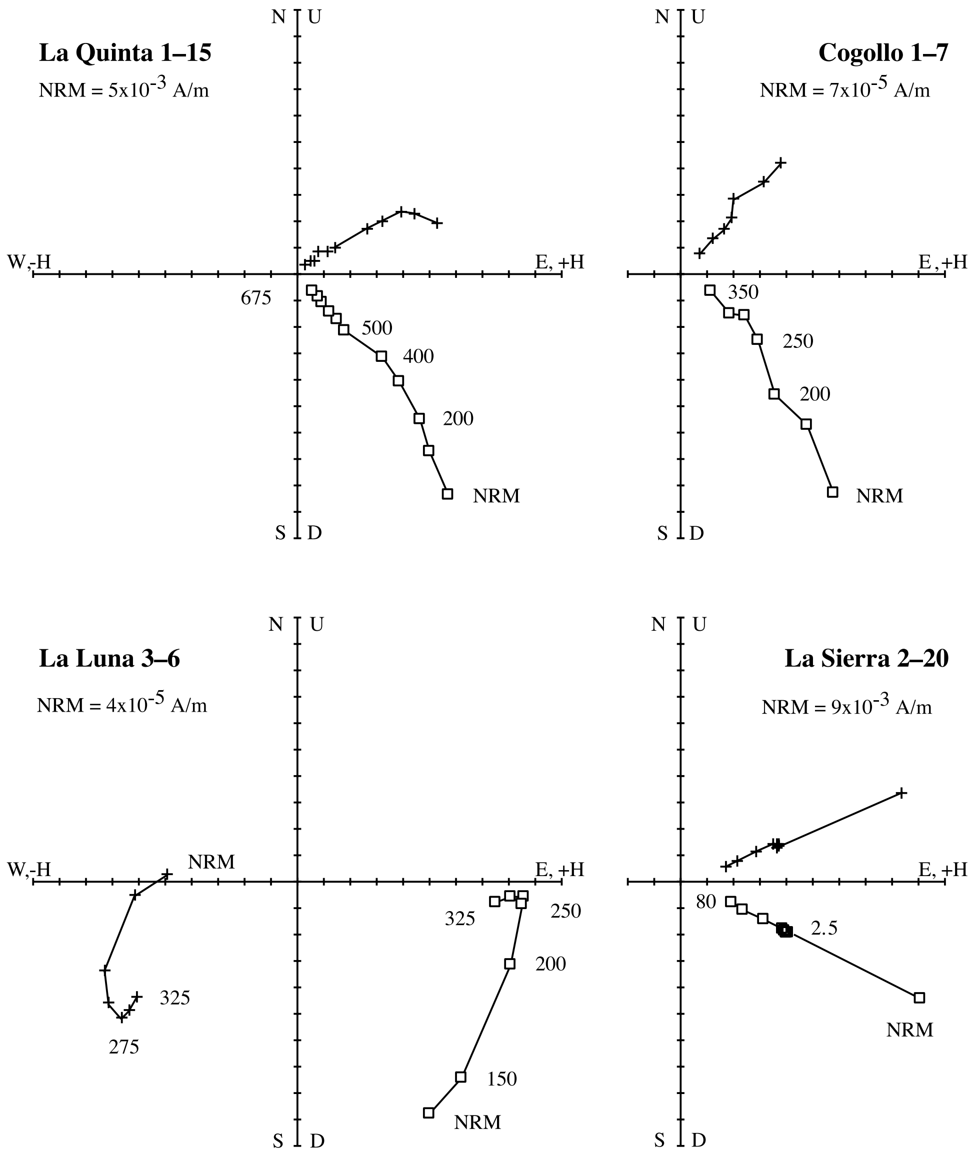


Figure 3. Vector component diagrams of samples from La Quinta Formation, Cogollo Group, and La Luna and La Sierra Formations. The numbers in the graphs indicate the demagnetization temperatures in degrees Celsius except for the La Sierra sample, where the values are the demagnetization field in millitesla. Crosses are the projection onto the north-east-south-west (N-E-S-W) plane, and open squares lie in the up-down-horizontal (U-D-H) plane. NRM = natural remanent magnetization.

magnetized horizons were encountered, although the biostratigraphic age range places the La Luna Formation entirely within the long, normal Cretaceous chron (Renz, 1959; Gonzáles de Juana et al., 1980; Harland et al., 1990). Because La Luna strata are dipping rather uniformly, no fold test can be applied to aid in determining the time of magnetization. We also observed reversals in La Luna beds in the Mérida Andes (Castillo et al., 1991). Remagnetization of the La Luna Formation is a possibility, but the fact that the magnetization is carried by magnetite in the samples from the Perijá Mountains and by hematite in the Andean samples (Figure 5) argues against this option. Tarduno et al. (1992) reported reversely magnetized intervals in mid-Albian limestones from Italy; thus, it is reasonable to speculate that the La Luna samples record the same events.

The youngest strata sampled are the middle to upper Eocene sandstones of the La Sierra Formation, which were collected near Machiques in the Rio Negro valley. The samples from site 2 were heated to 150° only before switching to alternating field demagnetization because these samples were heavily stained by a nearby oil seep.

DISCUSSION

These new paleomagnetic results constitute a solid data set. The 95% circles of confidence for the individual sites range from 5.1 to 13.4°. More importantly, the data set is internally consistent, in marked contrast to results obtained by Maze (1983). All site mean directions point northeasterly, with two sites in the La Luna Formation being of opposite polarity

Table 1. Statistical parameters of paleomagnetic analyses.

Site	N/N	R	Decl	Incl	k	α_{95}	Lat	Long
La Sierra Formation								
La Sierra 1	14/1	13.690	15.1	18.9	41.9	6.2		
		13.690	45.9	17.5	41.9	6.2	44.7	13.5
La Sierra 2	14/0	13.780	6.3	43.7	59.0	5.2		
		13.780	68.9	24.4	59.0	5.2	22.6	7.6
La Sierra 3	15/0	14.682	0.9	31.1	44.1	5.8		
		14.682	54.9	29.3	44.1	5.8	36.3	5.3
La Luna Formation								
La Luna 1	14/2	13.250	13.3	23.6	17.3	9.8		
		12.235	24.3	36.8	17.0	9.9	63.8	348.1
La Luna 3	11/3	10.257	239.4	9.3	13.5	12.9		
		10.257	233.8	14.6	13.5	12.9	33.5	33.7
La Luna 4	9/3	8.564	36.1	17.2	18.4	12.3		
		8.572	46.4	20.7	18.7	12.2	44.4	12.7
La Luna 5	12/4	11.058	234.3	−7.3	11.7	13.3		
		11.034	239.9	−11.3	11.4	13.4	30.6	17.0
Cogollo Group								
La Gé	23/3	21.699	20.6	33.8	16.9	7.6		
		21.566	30.1	27.1	15.3	8.0	60.3	6.7
Rio Apon 1	16/0	15.717	5.6	23.9	53.1	5.1		
		15.717	38.3	55.1	53.1	5.1	46.9	334.8
Rio Apon 2	13/0	12.333	−2.4	22.2	18.0	10.0		
		12.331	41.4	45.1	17.9	10.1	47.6	348.6
La Quinta Formation								
La Quinta	20/4	18.014	15.9	26.3	9.6	11.1		
		19.088	48.1	26.8	20.8	7.3	42.9	7.5
Site mean	11/0	10.316	47.4	26.1	14.6	12.4		
Pole mean	11/0	10.578			23.7	9.6	44.1	6.6

N/N is the number of samples used/rejected; R is the resultant vector; Decl is declination; Incl is inclination; k is Fisher's precision parameter; α_{95} is the radius of the 95% circle of confidence; Lat and Long are the north latitude and east longitude of the pole position. For each entry, the first line shows the results in situ, the second line after tilt correction.

(Figure 6). Because the motion of the South American Plate has been east-west since the opening of the South Atlantic Ocean (e.g., Ladd, 1976), the direction of magnetization of rocks of Cretaceous age and younger will be the same. This was pointed out by MacDonald and Opdyke (1984) and verified by our data from the Mérida Andes. Thus, it is proper to combine our paleomagnetic data into one mean value despite their spread in age. The mean of the tilt-corrected site means has a declination of 47.4° and an inclination of 26.1° with an α_{95} = 12.4°.

Figure 7 compares the pole positions from the Perijá Mountains with the mean pole position from the Mérida Andes, which is based on nine Mesozoic sites (Castillo et al., 1991). The clockwise rotation of the Perijá sites is striking. Using the formalism of Beck (1980) and Demarest (1983), the mean Perijá direction is rotated relative to the Andes mean by R = 49.8° ± 11.8°. The change in latitude is statistically insignificant (F = −10.9° ± 12.6°).

The simplest interpretation of these data calls for a ~50° clockwise rotation of the entire Perijá Range. Using the southern end of the Perijá Mountains as the point of rotation would make these mountains a linear extension of the Santander Massif. In this scenario, the northern part of the Perijá near the

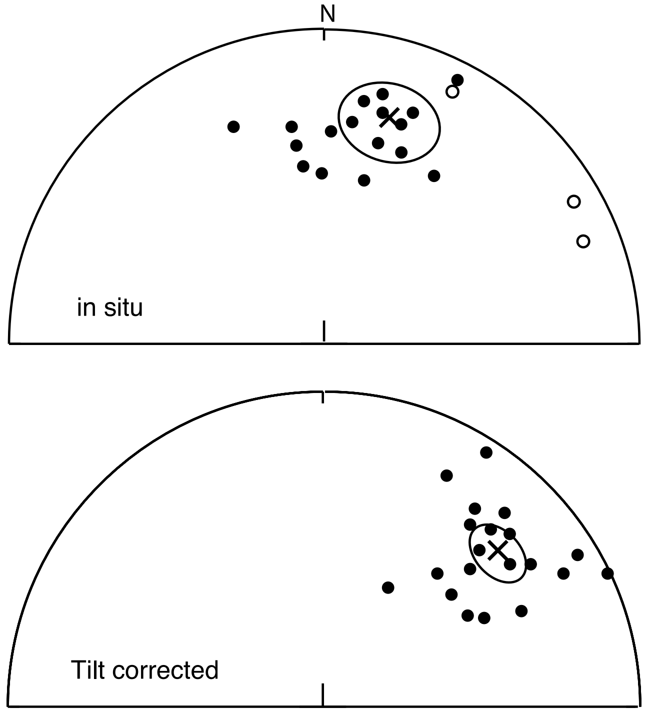


Figure 4. Equal-area projections of the directions of magnetization for La Quinta samples before and after tilt correction, with their circles of 95% confidence. The directions cluster better after tilt correction at the 99% significance level.

inlet to Lake Maracaibo would then have moved toward the Mérida Andes by about 200 km, which should be recognizable in significant folding and thrusting. Based on extensive seismic evidence, such major shortening did not occur (e.g., Gonzáles de Juana et al., 1980; Audemard, 1991), and this interpretation thus has to be rejected.

But the observations can be readily accounted for by using a model of distributed deformation by faulting, such as proposed by McKenzie and Jackson (1983). In this model, blocks of width "w" lie between two parallel faults, and compression across the fault zone will cause the blocks to rotate. Figure 8a shows the model at time 0 and Figure 8b depicts the area after deformation and identifies some of the faults of the sampling area. The paleomagnetic data yield the rotation angle ϕ and the width of the blocks can be estimated from the geological map (5 to 10 km). The initial angle between the blocks and the bounding faults is α. The zone of deformation is well-defined in the west by the Perijá-Tigre Fault but less certain in the east because of alluvial cover. We use the Rosario-Alturitas Fault as the eastern delimiter. The strike-slip offset along the faults is given by

$$d = \frac{\sin\phi}{\sin\alpha\,\sin(\alpha-\phi)} * w$$

and the shortening across the shear zone is

$$s = \frac{\sin\alpha - \sin(\alpha-\phi)}{\sin\alpha} * 100$$

Table 2 lists the strike-slip displacement between the blocks and the amount of shortening of the

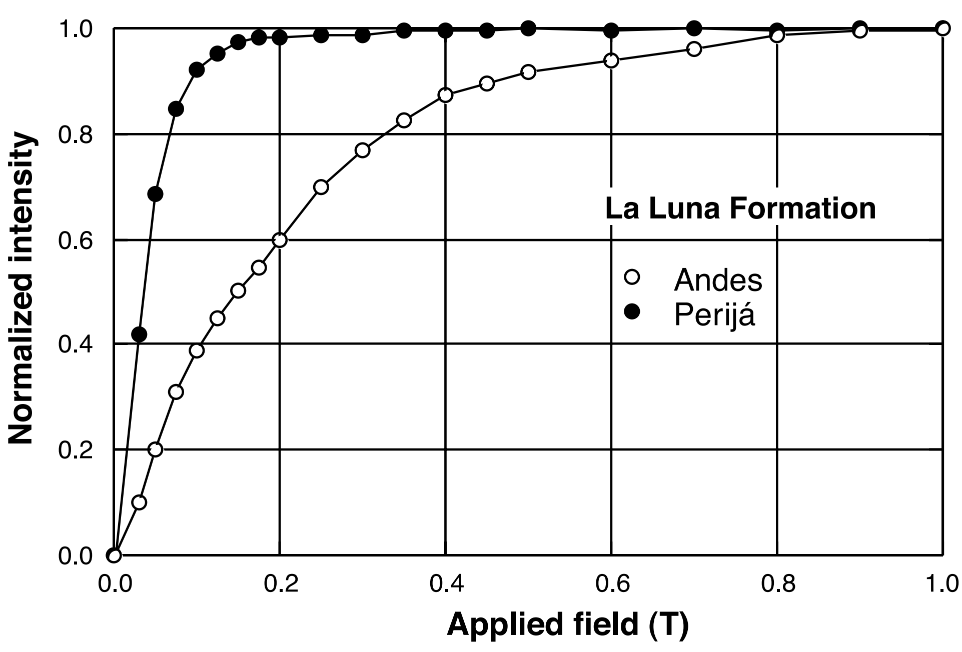


Figure 5. Isothermal remanent magnetization (IRM) acquisition for samples from the La Luna Formation. The sample from the Perijá site saturates in an applied field of about 0.2 T, implying that magnetite is the carrier of the magnetic remanence. The magnetic mineral in the Andean sample is hematite.

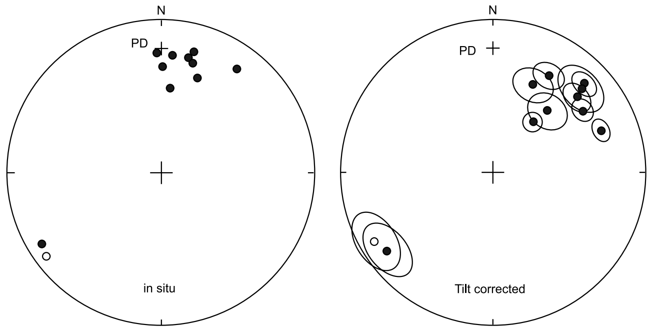


Figure 6. Schmidt equal-area projections of the site mean directions of magnetization. The tilt-corrected means are shown with their error circles (α_{95}). PD indicates the direction of the present dipole field.

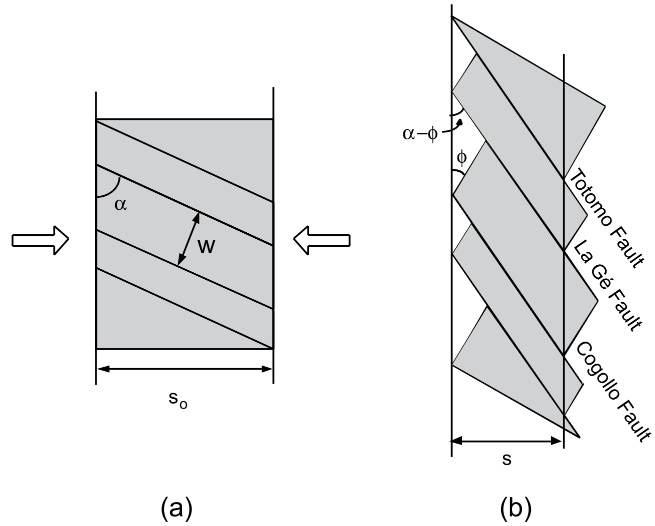


Figure 8. Block model for distributed deformation by faulting (after McKenzie and Jackson, 1986). (a) At time 0, the fault zone has a width s_0. Individual fault-bounded blocks have a width w and intersect the limiting faults at an angle α. (b) Compression across the fault zone will cause the blocks to rotate. The amount of rotation (ϕ) is determined by the paleomagnetic analyses. The strike-slip offset d and the new width s can then be calculated.

deformation zone for two block widths. For the angle α, we use values of 85° and 80°, values that were estimated from the geologic map by restoring the observed rotations. The shortening across the deformation zone was calculated using a value of 30 km for its initial width, a value that is close to the distance between the Perijá-Tigre and Rosario-Alturitas Faults. The parameters are given for the mean paleomagnetic rotation and its upper and lower error limits. Based on these model calculations, the strike-slip displacement between the blocks is about 10 km and the shortening could be as small as 8 km or as large as 20 km.

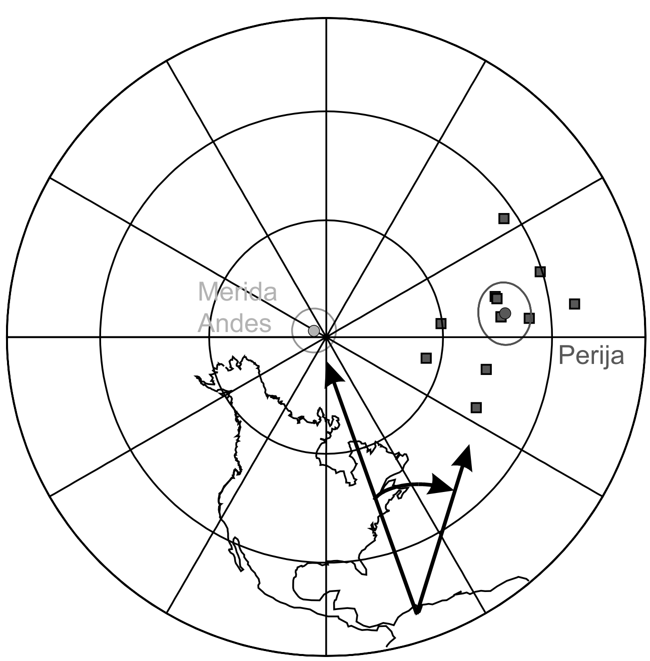


Figure 7. Comparison of the site poles from the Perijá Mountains with the mean pole of nine Mesozoic sites in the Mérida Andes. The poles imply that the Perijá sites have undergone a 50° clockwise rotation relative to the Mérida Andes.

Such values are well within the constraints of the known geology of the area. For example, Audemard (1991) estimates the shortening along a northwest-southeast section across the central part of the Perijá Mountains to be 26 km, based on an analysis of seismic data with well control.

The paleomagnetic data establish the timing of these block rotations as post-La Sierra Formation; i.e., post-late Eocene. The observed rotations could well be the results of Neogene compression, identified by Audemard (1991) based on structural analyses.

CONCLUSION

Paleomagnetic analyses of sedimentary rocks of Jurassic through Eocene age from the Perijá Mountains yield an internally consistent data set. The mean pole position of 11 site poles lies at 44.1° N, 6.6° E and has an error of A_{95} = 9.6°. These data indicate a 50° ± 12° clockwise rotation of the sampling sites relative to the Mérida Andes. These observations are interpreted to be the result of Neogene compression that caused the rotation of fault-bounded blocks. Model calculations suggest a shortening of between 8 and 20 km across the eastern portion of the Perijá Mountains.

Table 2. **Results of model calculations for the Perijá deformation zone using the paleomagnetically determined rotation of ϕ = 49.8° ± 11.8°. The strike-slip displacement between the blocks and the shortening across the fault zone are listed for two block widths and two values for α, the initial angle between the faults. See Figure 8 for definition of these parameters.**

ϕ	α	*Block width km*	*Displacement km*	*Shortening km*
49.8°	85°	5	6.7	12.6
		10	13.3	12.6
	80°	5	7.7	14.7
		10	15.4	14.7
61.6°	85°	5	11.1	18.0
		10	22.2	18.0
	80°	5	14.1	20.4
		10	28.3	20.4
38.0°	85°	5	4.2	8.0
		10	8.5	8.0
	80°	5	4.7	9.6
		10	9.3	9.6

ACKNOWLEDGMENTS

Fieldwork for this project was done in 1988 through 1990. We appreciate the support of National Science Foundation (INT-8608620) and CONICIT (Venezuela) and the supplemental funding by the Melon Foundation. We benefited from discussions with many Venezuelan researchers, particularly Felipe Audemard, and we thank Brooks Ellwood and Bill MacDonald for thoughtful reviews.

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