SUBDUCTION OF THE CARIBBEAN PLATE
AND BASEMENT UPLIFTS IN THE
OVERRIDING SOUTH AMERICAN PLATE

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Abstract. The new tectonic interpretations presented in this paper are based on geographic field mapping and gravity data supplemented by well logs, seismic profiles, and radiometric and earthquake data. The present Caribbean-South American plate boundary is the South Caribbean marginal fault, where subduction is indicated by folding and thrusting in the deformed belt and a seismic zone that dips 30° to the southeast and terminates 200 km below the Maracaibo Basin. The Caribbean-South American convergence rate is estimated as $1.9 \pm 0.3$ cm/yr on the basis of the 390-km length of the seismic zone and a thermal equilibration time of 10 m.y. The Caribbean-South American convergence has produced a northwest-southeast maximum principal stress direction $\sigma_1$ in the overriding South American plate. The mean $\sigma_1$ direction for the Maracaibo-Santa Marta block is $310^\circ \pm 10^\circ$ based on earthquake focal mechanism determinations, and structural and gravity data. On the overriding South American plate, basement blocks have been uplifted 7-12 km in the last 10 m.y. to form the Venezuelan Andes, Sierra de Perija, and the Colombian Santa Marta massif. Crystalline basement of the Venezuelan Andes has been thrust to the northwest over Tertiary sediments on a fault dipping about 25° and extending to the mantle. In the Sierra de Perija, Mesozoic sediments have been thrust 16-26 km to the northwest over Tertiary sandstones along the Cerrejon fault. A thrust fault dipping $15^\circ \pm 10^\circ$ to the southeast is consistent with field mapping, and gravity and density data. The Santa Marta massif has been uplifted 12 km in the last 10 m.y. by northwest thrusting over sediments. The basement block overthrusts of the Perijas, Venezuelan Andes, and the Santa Marta massif are Pliocene-Pleistocene analogs for Laramide orogenic structures in the middle and southern Rocky Mountains of the United States. The nongeanticlinal basement block uplifts along low-angle thrust faults reveal horizontal compression in the overriding plate over 500 km from the convergent margin. Present-day east northeast-west southwest ($080^\circ$) compression is indicated by earthquake focal mechanisms and strike slip motion on the Bocono fault. These earthquakes are intraplate deformation associated with east-west ($080^\circ$) Nazca-South American convergence.

INTRODUCTION

The Caribbean-northwestern South American plate boundary has been the most controversial and difficult Caribbean boundary to interpret tectonically (Figures 1 and 2). The high seismicity and Holocene...
displacement on the northeast trending Bocono fault (Figure 2) have prompted some to interpret the Bocono fault zone as the Caribbean-South American plate boundary [Molnar and Sykes, 1969; Dewey, 1972]. Kafka and Weidner [1981] determined surface wave focal mechanisms for five earthquakes near the Bocono fault zone. The determinations were consistent with compression in an east-west direction, which they interpreted as the direction of Caribbean-South American convergence. Present-day northwest-southeast convergence across the Caribbean-South American plate boundary, however, has been deduced from North American-South American relative plate motions [Ladd, 1976] combined with Caribbean-North American relative motion [Jordan, 1975; Minster and Jordan, 1978]. Northwest-southeast Caribbean-South American convergence is also suggested by compressive deformation in the southern Caribbean [Krause, 1971; Shepard, 1973; Case, 1974; Bowin, 1976; Talwani et al., 1977] and the Venezuelan Andes [Shagam, 1975]. In this paper additional geological, gravity, and seismic evidence for northwest-southeast convergence is presented.

The integrated interpretation of the regional tectonics of northwestern South America offered in this paper explains both the seismicity on the Bocono fault zone and the northwest-southeast compression. The dextral strike slip motion and high seismicity on the Bocono fault zone are interpreted as intraplate deformation associated with east-west convergence of the Nazca and South American plates. The northwest-southeast compression is related to southeastward subduction of the Caribbean plate beneath South America.

In Colombia the Andean chain branches into three distinct ranges: the Western, Central, and Eastern cordilleras. Near the Venezuelan border, the Eastern Cordillera separates into the Venezuelan Andes and the Santander massif. The Venezuelan Andes trend northeast (Figure 2) to meet the Caribbean mountain system of Central and Eastern Venezuela. The Santander massif trends northwest (340ø) and is
Fig. 2. Tectonic reconstruction of the Maracaibo-Santa Marta block during the Pliocene (3 m.y.). Hachured areas are major uplifts with pre-Tertiary rocks exposed. Depths to the proto-Andean unconformity (25 m.y.) are given in thousands of feet; the contour interval is 2000 feet [Zambrano et al., 1971]. Northwest-southeast line is the line of section for Figures 9 and 10. Structural symbols are as given in Figure 4.

continuous with the northeast trending (025°) Sierra de Perija. The Perijas continue northeast to the Oca fault zone where the range ends at the edge of the Goajira plains. The Santa Marta massif (Sierra Nevada de Santa Marta) (Figure 2), aligned with the Central Cordillera of Colombia, is the highest range in Colombia (about 5800 m) and has one of the highest topographic reliefs (over 9 km) of any seaside mountain in the world.

GRAVITY MAP

A Bouguer gravity anomaly map (Figure 3) was compiled for the study area from new observations by the authors in the Perija region [Kellogg, 1982a] and published sources [Case and MacDonald, 1973; Rodriguez and Craterol, 1975; Bowin, 1976; Bonini et al., 1977; Bermudez and Acosta, 1978]. Figures 9 and 10 are an 800-km cross section. The major features of the map are, from the southeast to the
northwest: a −160 mGal closure near Bobures on the northwest Andean flank; a gradual rise to the Perija front (−50 mGal) (Figure 10); a minor low over the Cesar Valley; a pronounced high from +50 mGal to +130 mGal over the Santa Marta massif; and offshore a low near zero rising to +200 mGal and greater in the Colombian Basin (Figure 9). Steep gradients are present across the Oca and Santa Marta fault systems bounding the Santa Marta massif (Figure 3).

SIERRA DE PERIJA

Along its entire length of over 200 km, the crest of the Sierra de Perija forms the International Boundary between Venezuela and Colombia and also the divide between the Maracaibo Basin of Venezuela and the Cesar Valley of Colombia (Figure 2). Lower Cretaceous limestones and conglomerates cap the crest of the range at elevations of up to 3650 m (Figure 4) uplifted 7 km above the same formations in the flanking basins. These beds dip gently to the southeast at about 6°. At the mountain front on the east flank of the Perijas the bedding dip changes abruptly to almost vertical, forming prominent flatirons and disappearing under the thick Tertiary sediments of the Maracaibo Basin.

The basement block or 'germanotype' tectonic style of the Sierra de Perija is a late Cenozoic analog for that of the Laramide orogeny (40-70 m.y.) in the central and southern Rocky Mountains of the United States. The Mesozoic limestones that cap much of the Perijas are arranged in a characteristic straight grid pattern with broad regions of uniform strike and dip separated by narrow zones of steeper dips. Deformation is concentrated in narrow fault zones and prominent monoclines along the margins of the Perijas. Crystalline basement rock is involved in the structures on the east side of the Sierra. The Bouguer gravity anomaly pattern in the Perijas consisting of broad, gentle gradients separated by sharp, narrow gradients [Kellogg, 1982a] is similar to gravity patterns in the Laramide tectonic province. The basement tectonic style of the Sierra de Perija is also analogous to that of the Venezuelan Andes, the Sierra Nevada de Santa Marta of Colombia, and the Maracaibo Basin (Figure 2) [Bonini et al., 1982]. (For a more detailed discussion of the basement block tectonic style see Kellogg [1981].)

Most previous interpretations of the tectonic style of the Perijas involved uplift on high-angle reverse faults with minimal horizontal displacement [e.g., Miller, 1962]. Only Dufour [1955] and Castro-Orjuela [1970] have proposed any major overthrusting on low-angle thrust faults. Detailed geologic mapping and gravity data [Kellogg, 1981, 1982a], however, support low-angle northwestward overthrusting as the structural origin for the Perija mountain range. The overthrusting occurred on the southeast-dipping Cerrejon-Manaure thrust fault.

Field relations observed along the Cerrejon thrust (Figure 4) suggest that Cretaceous limestones and Jurassic red sandstones have been thrust to the northwest over Paleocene to lower Eocene sandstones and coals [Castro-Orjuela, 1970]. Streams have downcut through the limestone, exposing Tertiary sandstones beneath the thrust sheet. The principal evidence for a low-angle dip on the fault is that the sinuous fault trace follows topographic contour lines. On the basis of detailed field mapping of the relation between the Cerrejon fault trace and the topography, the dip on the fault was estimated as 17° ± 12° [Kellogg, 1981]. The apparent bedding dips are shown in the geological cross section in Figure 5.

Gravity observations by A. Bermudez and J. N. Kellogg in the vicinity of the Cerrejon fault resulted in the discovery of a gravity low over the fault (Figure 5). The Bouguer gravity low is most likely caused by the low-density Tertiary sediments of the Rancheria
Fig. 3. Bouger gravity anomaly map of western Venezuela and northeastern Colombia [Bonini et al., 1981]. A density of 2.67 g/cm$^3$ has been used in the mass correction for land data and also to reduce sea station free air anomalies to water-corrected Bouger anomalies. Contour interval = 10 mGal onshore and 50 mGal offshore.
Fig. 4. Geologic location map of the Sierra de Perija (see facing page).
The center of the low, however, is located directly over the Cerrejon fault. It is probable, therefore, that there are Tertiary sediments under the thrust fault. This gravity information can be used to constrain estimates of the dip on the Cerrejon fault.

Measured densities from 47 rock samples were used to construct a density model. The density-depth relation for shales and sandstones was deduced from well sample measurements by Hedberg [1936], a velocity survey in the Conception field (east of La Paz, Venezuela) (well C-150, Compania Shell de Venezuela, Ltd.), and the velocity-density relations given in Woollard [1962]. The effects of irreversible compaction were not considered for shales and sandstones, so the density lines for units with major proportions of shale and sandstone were drawn parallel to topography in Figure 5. Beneath the Cesar Valley the limestones of the Cogollo Group (Kcg) and all underlying units were assumed to be irreversibly compacted and were given a density of 2.70 g/cm³ irrespective of depth. If irreversible compaction is an important factor in the shales and sandstones, the true density lines would tend to follow the structure more than they do in the present model. Figure 5 also shows the terrain-corrected observed gravity anomalies. With a density contrast of approximately 3.0 ± 0.1 g/cm³ across the Cerrejon fault, the model gravity anomaly was calculated for fault dips of 7°, 15°, and 30°. The density contrast of 0.3 g/cm³ was maintained across the fault and density lines were extended parallel to topography. For a density contrast of 0.3 g/cm³, the calculated gravity for a 15° dip on the fault best fits the observed gravity. The uncertainty for the density contrast is about ± 0.1 g/cm³, which corresponds to the range from 5° to 25° or ± 10°.

Map Symbols

- **30°**: Contact or marker bed, showing dip direction and in degrees where observed
- **80°**: Contact or bed overturned
- **Horizontal bedding**
- **60° D U**: Fault, showing dip (D, downthrown side; U, upthrown side)
- **Fault, showing relative horizontal movement**
- **Thrust fault; sawteeth on upper plate**
- **9° 15°**: Anticline (top) and syncline, showing trace of axial plane and plunge of axis
- **Axial trend of small chevron folds**
- **Strike and dip of foliations**
- **78°**: Strike and dip of joints
- **23°**: Trend and plunge of striations on slickensides
If a broad syncline with the approximately horizontal southeast limb shown in Figure 5 is assumed with a fault dip of $15^\circ \pm 10^\circ$, the vertical uplift on the Cerrejon thrust would have been $4.5 \, \text{km}$ with a horizontal displacement of $16 \pm 8 \, \text{km}$. This is sufficient to explain the post lower Eocene uplift of the northern Sierra de Perija.

The deep geologic cross section of the Sierra de Perija shown in Figure 6 includes the line of section of Figure 5. The cross section extends from the La Paz anticline in the Maracaibo Basin of Venezuela northwest across the northern Sierra to the Cesar Valley in Colombia (Figure 4). The cross section was based on mapping by Creole Petroleum Corporation geologists (Creole Petroleum Corp., map C-2 [1962], Castro-Orjuela [1970], and Kellogg [1981] in Colombia and M. L. Miller (Creole Petroleum Co., map C-2-D [1957]), Nogueira et al. [1972], Gonzalez-Padilla [1975], Bellizzia et al. [1976], and Kellogg [1982a] in Venezuela. Well-log data are from the Caribbean Petroleum Co., Mene Grande Oil Co., and Compania Shell de Venezuela, Ltd.

In the structural solution in Figure 6, the Cerrejon thrust is interpreted as a step-up fault from a decollement at a depth of $8 \, \text{km}$. A dip of $8^\circ$ to the southeast is predicted for the Cerrejon thrust in Figure 6 to explain the uniform gentle dips observed at the surface on the southeast flank of the Perijas. This solution is within the uncertainties of the near-surface dip estimates for the Cerrejon thrust of $17^\circ \pm 12^\circ$ and $15^\circ \pm 10^\circ$ based on geological and gravity data, respectively. The total predicted horizontal shortening for the Perijas derived from the model in Figure 6 is $46 \pm 13 \, \text{km}$.

The orientations of folds and reverse faults proved to be relatively consistent in all Tertiary units studied throughout the central and northern Sierra. Field measurements were made by Kellogg...
Fig. 6. Deep geologic cross section of the northern Sierra de Perija. The location of the section line is shown in Figure 4 (Cerrejón). All Tertiary units are shown in the circle pattern; the Cretaceous Ogolilo Group is in black; and pre-Cretaceous units are shown in the screened pattern.
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Fig. 7. Northwest-southeast compressive trends from the orientations of folds and reverse faults in the Perijas. Poles are plotted on an equal-area lower hemisphere projection.

[1981] for 20 fold hinge lines, 17 fold axial surfaces, and 11 reverse faults with displacements on the order of several meters. The folds and faults were observed in Jurassic through Eocene formations along the eastern frontal monocline and along the Cerrejon, Tigre, and Oca fault zones (Figure 4). The orientations of the folds and reverse faults were used to calculate a maximum principal stress \( \sigma_1 \) direction for the Perijas.

An estimate of the direction of maximum principal stress may be obtained from the poles to the axial planes of the folds, provided the folds were formed primarily by buckling with minimal shear folding. The trends of the hinge lines, however, are orthogonal to the maximum principal stress, so 90° were added to the trends. Although the plunges of the hinge lines may be used to estimate the intermediate principal stress \( \sigma_2 \) orientation, they do not contain additional information about the maximum compressive stress \( \sigma_1 \) orientation, so the plunges were replaced by 0.0. The average dip observed for the reverse faults was 44°, so the direction of \( \sigma_1 \) was estimated as 45° to the fault planes; \( \sigma_2 \) was assumed to be horizontal. (Forty-five degrees were subtracted from the plunge of the pole normal to the fault plane. If the resulting plunge was negative, i.e., upper hemisphere, 180° were subtracted from the trend and the sign of the plunge changed to positive, i.e., lower hemisphere.) The resulting distribution of lines (Figures 7 and 8) is approximately bimodal: a tightly clustered northwest-southeast horizontal trend and a loosely clustered north northeast-south southwest trend. All 34 lines in the northwest-southeast cluster (096°-135° and 280°-320°) are shown in Figure 7. The north northeast-south southwest trending lines (360°-020° and 175°-226°) are shown in Figure 8. Lines trending 060° from two folds were omitted because their trend diverged significantly
Fig. 8. North northeast-south southwest compressive trends from the orientations of folds and reverse faults in the Perijas. Poles are plotted on an equal-area lower hemisphere projection.

(over 46°) from the NNE-SSW mean direction and (about 59°) from the NW-SE mean direction.

Fisherian statistics defining the distribution of points on a sphere were developed as a statistical model against which paleomagnetic observations could be tested [Fisher, 1953; Tarling, 1971]. The model has direct applicability for testing structural models. It simulated the two-dimensional Gaussian (normal) distribution in three dimensions whereby circularly symmetric points on a sphere (directions or poles) could be described in terms of a probability density $P$ given by:

$$K
P = \frac{1}{4\pi \sinh K} \exp (K \cos \theta)$$

where $\theta$ is the angle between the observed individual directions and the true mean direction and $K$ is the concentration parameter varying from 0 for a perfectly random distribution to infinity for identical directions. The concentration parameter can be estimated as

$$K \perp k = \frac{N - 1}{N - \overline{R}}$$

where (the resultant vector) $\overline{R}$ is the sum of $N$ vectors (directions or pole positions) of unit length using direction cosines. On this model the reliability of the observed mean direction can be defined by measuring the radius $\alpha$ of a circle on the sphere's surface, centered on the observed mean direction, within which there is a particular
TABLE 1. Perija Maximum Principal Stress Directions Estimated From Fold and Reverse Fault Data Shown in Figures 7 (N = 34) and 8 (N = 11)

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<th>R</th>
<th>Kappa</th>
<th>Circular Standard Deviation</th>
<th>α 95</th>
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**Fisherian Statistics**

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<th>k₂</th>
<th>Min.</th>
<th>Max.</th>
<th>Bingham 95%</th>
</tr>
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<td>3.5</td>
<td>16.34</td>
<td>-8.41</td>
<td>1.8</td>
<td>2.6</td>
<td>4.5</td>
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<tr>
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<td>-6.32</td>
<td>5.4</td>
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</tr>
</tbody>
</table>

**Bingham Statistics**

Eigenvalues for the Bingham statistics on the 34-line data are 30.716, 2.203, and 1.081. Eigenvalues for the 11-line data are 9.104, 0.997, and 0.900.

The probability P of the true mean direction lying, i.e., the cone of confidence:

\[ \alpha = \cos^{-1} \left( 1 - \frac{N - \hat{R}}{\hat{R}} \right) p^{-1/(N-1)} - 1 \]

If the probability P is taken to be 0.05, there is a 20 to 1 chance of the true mean direction lying within α 95 degrees of the observed mean direction. The two precision parameters, k and α 95, can therefore be used as measures of the reliability of the observed mean direction of a group of directions which have a circularly symmetric Fisherian distribution, the highest reliability being for the largest k and the smallest α 95. The circular standard deviation (c.s.d.), the radius of the circle centered on the mean direction that encloses 63% of the points, is a measure of the magnitude of the scatter of directions about their mean.

Applying Fisherian statistics to the 34 NW-SE trending data shown in Figure 7 gives (Table 1) a subhorizontal (plunge = 2.3°) NW-SE trend (298.8°-118.8°). The low α 95 (6.3°) and high k (16.4) suggest high reliability for the calculated mean direction. The circular standard deviation (c.s.d.) (20°) indicates low to moderate scatter of directions.

Application of Fisherian statistics to the 11 NNE-SSW trending data shown in Figure 8 gives (Table 1) a mean direction of trend = 13.8°, plunge = 10.9°. The higher α 95 (15.6°) and lower k (9.5) indicate less reliability for the NNE-SSW mean than for the NW-SE mean direction. A higher c.s.d. (26.4°) is caused by the greater scatter of directions in the NNE-SSW data.

Bingham statistical parameters provide a better approximation than Fisherian statistical parameters for elongate data sets [Bingham, 1964; Onstott, 1980]. Application of the Bingham density function to
the structural data shown in Figures 7 and 8 gives the results listed in Table 1. One calculated Bingham mean trend direction (298.8°) is identical to the Fisherian mean trend direction; the other differs by less than a degree. The small differences between the concentration parameters k1 and k2 indicate that the data sets are not very elongate and are approximately Fisherian circularly symmetric distributions. Both Bingham and Fisherian statistical models have great potential applicability for the quantitative analysis of structural data.

The statistical parameters indicate that the northwest-southeast trending 299° ± 6° ± 5° mean direction is a reliable estimate of the maximum compressive stress direction σ1 in the Perijas based on the structural data available. Cenozoic northwest-southeast shortening in the Perijas is also suggested by geological and geophysical data from the Cerrejon and Rio Cachiri areas [Kellogg, 1982a]. The NNE-SSW trending 014° ± 16° ± 5° mean direction is a less reliable estimate of the secondary compressive stress direction in the Perijas.

The major uplift of the Sierra de Perija occurred during the Pliocene-Pleistocene Andean orogeny [Kellogg, 1982a, b]. The age of uplift can be inferred from stratigraphic relationships and from apatite fission-track age data. (1) Upper Miocene formations are conformably folded in the monocline along the southeast mountain front. (2) A Pliocene unconformity indicates interrupted deposition on the southeast flank of the Perijas [Young, 1958; Lexico Estratigrafico de Venezuela, 1970; Zambrano et al., 1971]. (3) A Pliocene age for the uplift of the Perijas is also supported by apatite fission-track age determinations of about 3 m.y. for samples of volcanics and granites from the Rio Palmar area (Figure 4) [Shagam, 1980].

SIERRA NEVADA DE SANTA MARTA

The Santa Marta massif (Sierra Nevada de Santa Marta) (Figure 2) is the highest range in Colombia (about 5800 m) and has one of the highest topographic reliefs (over 9 km) of any seaside mountain in the world. The structural relief is 12 km. The tremendous gravity high (180 mgal relative to the adjacent basins) over the Santa Marta massif (Figure 3) indicates that the crystalline massif is out of local isostatic equilibrium and may have been thrust to the northwest on the Oca and Santa Marta faults [Case and MacDonald, 1973; Bonini et al., 1982]. A low-angle Wind River-type thrust fault extending to the base of the crust (Figure 9) is consistent with the gravity data. The symmetry of the topography, structure, and gravity anomalies suggests that the thrusting was to the northwest (312°) forming approximately equal angles of 30° to 35° with the Oca and Santa Marta faults. This model also implies that the movements on the Oca and Santa Marta faults have been approximately contemporaneous and of similar magnitudes during the upper Tertiary. Based on the correlation of rock units across the Oca fault zone [Tschanz et al., 1974] and predicted oblique movement on the Oca fault produced by northwest-southeast shortening in the Perijas, the predicted total Tertiary oblique right lateral strike slip movement on the Oca fault zone east of the Perijas is 90 ± 8 km [Kellogg, 1981, 1982b]. Correlations of rock units across the Santa Marta fault demonstrate 100 – 115 km of left lateral Tertiary separation on the Santa Marta fault system (Tschanz et al., 1974).

To the west of Santa Marta, uplift, folding, and faulting resulted from continued lateral compression during the Pliocene Andean orogeny [Duque-Caro, 1978]. The newly active South Caribbean marginal fault zone became the new Caribbean-South America margin. Mud volcanism and plutonism began in the Sinu trench sediments located west of the Sinu fault.
Stratigraphic and fission-track data show that the major Cenozoic uplift of the Venezuelan Andes (Figure 2) occurred during the Pliocene-Pleistocene orogeny. Thick upper Miocene to Pliocene age conglomerates are found on the northwestern and southeastern flanks of the Andes [Lexico Estratigráfico de Venezuela, 1970]. Late Tertiary oxisols that formed near sea level were uplifted 3 km during the Pliocene-Pleistocene orogeny [Weingarten, 1977]. Rapid uplift is also suggested by the extensive Pleistocene terraces high above the present river base levels (R. Giegengack, Department of Geology, University of Pennsylvania, personal communication, 1979). Further proof of Pliocene uplift of the Venezuelan Andes is supplied by apatite fission-track age determinations on 15 rock samples ranging from 2 to 5 m.y. [Shagam, 1980]. By using this radiometric age data, Shagam calculated an uplift rate for part of the Pliocene (6-3 m.y.) of 0.8 mm/yr.

The gravity low associated with thick deposits of low-density sediments on the northwest flank of the Venezuelan Andes (Figures 2 and 3) can be explained by northwestward (320°) overthrusting of the Maracaibo Basin by crystalline rocks of the Andes [Bonini et al., 1982]. The Bonini et al. [1982] model is consistent with the observed gravity anomalies and involves a low-angle thrust (220-250°) extending into the mantle and overriding the Maracaibo Basin by 25 km (Figure 10).

Well-developed Pleistocene boulder terraces suggest rapid present-day uplift of the Sierra de Perija and Venezuelan Andes (R. Giegengack, Department of Geology, University of Pennsylvania, personal communication, 1979). On the northwest margin of the Sierra de Perija south of Manaure terraces are 200-300 m above the river base level. A crude estimate of the upper Pliocene-Pleistocene uplift rate for the Perijas can be made from the 2.7 m.y. apatite fission-track ages of Kohn [Shagam, 1980]. Assuming a 100°C closure temperature, an average crustal geothermal gradient of 25°C/km, and an erosion rate equal to the uplift rate, the uplift rate = 100/(25)(2.7) km/m.y. = 1.5 mm/yr. On the Cerrejon thrust fault (15° dip) this uplift rate

Fig. 9. Northwest-southeast section from the Colombian Basin to the Maracaibo Basin [Bonini et al., 1982]. Vertical exaggeration = 2:1. See Figure 2 for line of section.
would be equivalent to a horizontal slip rate of $\frac{1.5}{\tan 15^\circ} = 5.6$ mm/yr. A similar Pleistocene uplift rate of about 1.5 mm/yr would be calculated from the Andean fission-track data. This is considerably more rapid than the uplift rate of 0.8 mm/yr calculated by Kohn et al. [1982] for the Pliocene (3-6 m.y.), suggesting a possible increase in the Andean uplift rate during the Pleistocene.

PRESENT-DAY NORTHWEST-SOUTHEAST COMPRESSION

The northwest-southeast maximum principal stress direction that has characterized the Maracaibo-Santa Marta block and most of the Caribbean-South American margin throughout the Cenozoic continues to the present. Present-day northwest-southeast convergence across the Caribbean-South American plate boundary has been deduced from North American-South American relative plate motions [Ladd, 1976] combined with Caribbean-North American relative motion [Jordan, 1975; Minster and Jordan, 1978], and compressive deformation in the southern Caribbean [Krause, 1971; Shepard, 1973; Case, 1974; Bowin, 1976; Talwani et al., 1977]. Present-day northwest-southeast compression along the Caribbean-South American margin is also indicated by earthquake focal mechanism solutions that have been determined by using P wave first motions. Five of these focal mechanisms are the thrust fault solutions for events 1, 2, 3, 5, and 7 shown in Figure 11. The source parameters for the earthquakes are listed in Table 2. All the earthquakes were shallow (<70 km) except for event 2 (175 km).

Event 1 was produced by movement on a thrust fault at a depth of 58 km in the deformed belt 60-70 km southeast of the trace of the South Caribbean marginal fault [Vierbuchen, 1978]. In view of the northwest vergence of folds and thrusts in the deformed belt, the fault plane dipping shallowly to the southeast is probably the correct one.

Event 2 was a deep earthquake (175 km) located just southeast of the Perijas. The solution shown (O. Perez, W. R. McCann, and A. J. Murphy, Lamont-Doherty Geological Observatory, Palisades, New York, unpublished data, 1978) differs from the ambiguous strike slip solution of Dewey [1972]. The focal mechanism represents either west-northwest dipping compression at the base of the South American lithosphere or downdip (east-southeast) tension in the Caribbean lithosphere subducting beneath South America (Figure 12).
Fig. 11. Present-day tectonics of western Venezuela and northeastern Colombia. The dark arrow labeled Car-SoAm indicates the direction of convergence derived in this study for the Caribbean-South American boundary. The arrow labeled Nazca-SoAm indicates the direction of Nazca-South American convergence [Stauder, 1975; Minster and Jordan, 1978; Pennington, 1981]. The Nazca-South American plate boundary is located 80-100 km southwest of the map area. The eight earthquake focal mechanisms are based on P wave first arrivals. Solution 1 was calculated by Vierbuchen [1978]; 2 was by O. Perez, W.R. McCann, and A. J. Murphy (Lamont-Doherty Geological Observatory, Palisades, New York, unpublished data, 1978); 3, 4, 6, and 8 were by Dewey [1972]; and 5 and 7 were by Perez and Aggarwal [1980]. All plots are made on equal-area projections of the lower hemisphere of the focal sphere. Dark quadrants are compressional first motions. Source parameters are summarized in Table 2. Hachured areas are major uplifts with pre-Tertiary rocks exposed.

Event 3 was the result of shallow (29 km (CGS); 5 km (ISC)) thrust faulting just southeast of Lake Maracaibo on the northwest flank of the Andes. By using teleseismically recorded Rayleigh waves, Kafka and Weidner [1981] determined a very different focal mechanism from the body wave determination [Dewey, 1972] shown in Figure 11. The
TABLE 2. Summary of Source Parameters for Events 1-8 in Figure 11

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<td>5.7</td>
<td>175</td>
<td>9.55N</td>
<td>72.60W</td>
<td>280 (?)</td>
</tr>
<tr>
<td>2</td>
<td>Nov. 17, 1968</td>
<td>193605.8</td>
<td>4.8</td>
<td>29</td>
<td>9.00N</td>
<td>71.06W</td>
<td>297</td>
</tr>
<tr>
<td>3</td>
<td>May 13, 1968</td>
<td>041321.2</td>
<td>5.3</td>
<td>20</td>
<td>9.20N</td>
<td>70.28W</td>
<td>085</td>
</tr>
<tr>
<td>4</td>
<td>July 19, 1965</td>
<td>181215.8</td>
<td>4.8</td>
<td>26</td>
<td>8.08N</td>
<td>72.78W</td>
<td>045/07</td>
</tr>
<tr>
<td>5</td>
<td>March 5, 1975</td>
<td>091610.1</td>
<td>5.5</td>
<td>shallow</td>
<td>9.04N</td>
<td>69.95W</td>
<td>313</td>
</tr>
<tr>
<td>6</td>
<td>Sept. 2, 1964</td>
<td>091610.1</td>
<td>5.5</td>
<td>shallow</td>
<td>9.04N</td>
<td>69.95W</td>
<td>313</td>
</tr>
<tr>
<td>7</td>
<td>Composite focal mechanism solution for microearthquakes in Uribante-Caparo area</td>
<td>1979-1980</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Dec. 21, 1967</td>
<td>113724.5</td>
<td>5.4</td>
<td>29</td>
<td>7.04N</td>
<td>72.02W</td>
<td>087/297</td>
</tr>
</tbody>
</table>

The focal mechanisms in Figure 11 are based on P wave first arrivals. Solutions 3, 4, 6, and 8 were calculated by Dewey [1972]; solution 2 was calculated by O. Perez, W. R. McCann, and A. J. Murphy (Lamont-Doherty Geological Observatory, Palisades, New York, unpublished data, 1978); solutions 5 and 7 were calculated by Perez and Aggarwal [1980]; and solution 1 was calculated by Vierbuchen [1978]. The estimates of the maximum principal stress direction $\sigma_1$ are the azimuths of the axes of maximum pressure [Honda, 1962] for reverse fault solutions and 15° from the axes of maximum pressure for strike slip fault mechanisms.

[*] Body wave magnitudes $m_b$ are from the Earthquake Data Reports of the United States Coast and Geodetic Survey (USCGS) or the National Oceanic and Atmospheric Administration (NOAA).

[†] Depths are from the Earthquake Data Reports of USGS or NOAA and the Bulletin of the International Seismological Center (ISC).

Rayleigh wave solution was right lateral strike slip movement on a northeast-southwest trending fault similar to the solution for event 4 (Figure 11). The P wave data are not consistent with the surface wave solution for event 3, however. One possible alternative explanation for the conflicting data is that the earthquake consisted of multiple events. The P wave derived thrust fault solution fits well with movement on the Andean frontal thrust fault. On the basis of gravity data, Bonini et al. [1982] have proposed northwestward overthrusting of the Maracaibo basin by crystalline rocks of the Andes on a low-angle Wind River-type thrust fault extending into the mantle (Figure 10). Thrusting on the shallow eastward dipping nodal plane would be consistent with the Wind River-type fault model.

Event 5 was a shallow earthquake located east of the Venezuelan Andes in a zone of northeast trending thrust faults. The focal mechanism determination [Perez and Aggarwal, 1980] indicates northwest-southeast compression. Movement was probably on the northwest dipping fault plane (043; 45°NW) that is similar to the mapped faults in the area.

Event 7 is actually a composite of microearthquakes in the Uribante-Caparo area. The reverse fault focal mechanism in Figure 11 is a composite solution determined from data collected by the Uribante-Caparo microearthquake network [Perez and Aggarwal, 1980]. Perez and Aggarwal interpreted the southeast dipping (060; 58°SE)
nodal plane as the fault plane because the earthquake occurred in a zone of microearthquakes that dips steeply to the southeast.

The maximum principal stress direction ($\sigma_1$ in Table 2) can be estimated from the azimuths of the axes of maximum pressure [Honda, 1962] for reverse fault focal mechanisms. The $\sigma_1$ estimates for the shallow reverse faults in Figure 11 are $297^\circ$, $313^\circ$, $316^\circ$, and $317^\circ$. The estimates for three of the four events (5, 7, and 1) are clustered within a $4^\circ$ range from $313^\circ$ to $317^\circ$. These values correspond well with estimates of maximum compressive stress directions for the Santa Marta massif ($312^\circ$) and the Venezuelan Andes ($320^\circ$) based on structural and gravity data.

Few major historic earthquakes have occurred along the Oca fault system, but north of Sinamaica the fault does displace a series of Quaternary beach strandlines [Miller, 1962] and a shell horizon with an age of 2500 years (determined by carbon-14 dating) [Cluff and Hansen, 1969]. On May 3, 1849, an earthquake near Maracaibo with a maximum modified Mercalli intensity of VII damaged most large buildings and collapsed others [Cluff and Hansen, 1969]. Pleistocene activity on the Santa Marta–Bucaramanga fault system is demonstrated by deformation in Pleistocene terraces and offset stream patterns [Campbell, 1965].

Fault plane solutions for earthquakes in eastern Venezuela also indicate present-day northwest-southeast trending compression. The July 29, 1967 Caracas earthquake (event 10, Figure 1) consisted of at least three discrete sources of northwest-southeast ($350^\circ$) left lateral strike slip motion on an "en echelon" northwest-southeast trending ($310^\circ$) fault system [Rial, 1978]. If Coulomb failure with $\phi = 30^\circ$ is assumed, the maximum compressive stress direction can be estimated as forming an angle of $30^\circ$ with the fault plane and $15^\circ$ with the axis of maximum pressure [Honda, 1962] yielding a northwest-southeast ($320^\circ$) trending $\sigma_1$. By using Rayleigh wave radiation patterns, a very similar left lateral strike slip focal mechanism on a northwest-southeast ($350^\circ$) fault plane was determined for the small August 14, 1972 intra-Caribbean plate earthquake (event 9, Figure 1; Kafka and Weidner [1979]). Like the Caracas earthquake, $\sigma_1$ can be estimated as northwest-southeast ($320^\circ$). Microearthquake locations and new focal mechanisms indicate strike slip motion and normal faulting on the northwest-southeast trending ($315^\circ$) Los
Bajos-El Soldado fault system in addition to right lateral strike slip motion on the east-west El Pilar fault system [Perez and Aggarwal, 1981].

PRESENT-DAY EAST-WEST COMPRESSION AND THE BOCONO FAULT

Present-day east northeast-west southwest compression is indicated by the three focal mechanisms determined for events 4, 6, and 8 in Figure 11. It is also suggested by Quaternary displacement and major historic earthquakes on the Bocono fault.

The Bocono fault trends northeast-southwest (050°-055°) through the Venezuelan Andes. Rod et al. [1958] claims 30-70 km of cumulative right-lateral displacement on the fault. However, Shagam [1975] cites evidence that vertical displacement was predominant along the Bocono fault and that most of the lateral displacement occurred only in very recent times. Measurements of offset stream channels, terrace deposits, alluvial fans, and glacial moraines demonstrate up to 100 m of Holocene right lateral displacement [Cluff and Hansen, 1969; Schubert and Sifontes, 1970; and Giegengack et al., 1976]. The average rate of strike slip motion on the fault for the last 10,000 years is approximately 100 m/10^4 yr = 1 cm/yr. Up to 10 m of post glacial south-side-up vertical displacement has also been observed on the fault.

Numerous large historic earthquakes have occurred on the Bocono fault system including the great earthquake of March 26, 1812 (modified Mercalli intensity = XI; magnitude = 8) [Cluff and Hansen, 1969]. Since the advent of instrumental recordings the Bocono fault zone has been the most seismically active zone in northwestern Venezuela.

Event 4 (Figure 11) was a shallow (20-30 km) earthquake located on the trace of the Bocono fault. The P wave focal mechanism determined by Dewey [1972] is compatible with right lateral strike slip movement on the Bocono fault. An analysis of the Rayleigh wave radiation patterns confirms that the northeast-southwest trending nodal plane was the fault plane [Kafka and Weidner, 1981].

Event 6 occurred at shallow depths on the northwestern margin of the Santander massif in Colombia. The fault plane solution shown in Figure 11 indicates strike slip motion resulting from northeast-southwest compression [Dewey, 1972]. One nodal plane is parallel to the nearby Casigua fault, but the two possible solutions do not correlate well with any geologically mapped fault displacements in the area.

The focal mechanism determined for event 8 is similar to the one for event 4. The earthquake epicenter was located on the Colombia-Venezuela border in the complicated hinge area between the Venezuelan Andes, the Santander massif, and the Eastern Cordillera of Colombia. P wave first motions are consistent with strike slip motion either parallel to the Bocono trend or in a northwest-southeast direction [Dewey, 1972]. Surface wave radiation patterns indicate that the fault motion was right lateral strike slip on the northeast-southwest plane parallel to the Bocono [Kafka and Weidner, 1981]. This focal mechanism is consistent with lateral tear faulting associated with the mapped southwest dipping thrust faults in the area.

The 60°-65° angle between the Oca and Santa Marta fault systems suggests that Coulomb fracture criteria (φ = 30°) may be applicable to the major wrench faults delineating the Maracaibo-Santa Marta block. The maximum compressive stress direction 1 can then be estimated as 30° from the fault plane of a strike slip fault and 15° from the axis of maximum pressure in the focal mechanism. As surface wave and geologic information specify the probable fault planes for events 4 and 8, σ1 can be estimated as east-west (085° and 087°). Because of
a lack of surface wave and geologic information, \( \sigma_1 \) for event 6 may be either 045° or 075°, though 075° is more likely in view of the correlation with events 4 and 8. This compressive stress direction is very close to the east-west (080°) relative convergence vector for the Nazca and South American plates [Stauder, 1975; Minster and Jordan, 1978; Pennington, 1981]. The dextral strike slip motion on the Bocono fault is probably intraplate deformation associated with Nazca–South American convergence. However, there is clear geologic evidence for only very recent (Holocene) lateral displacement of about 100 m on the fault. That plus the similarity of \( \sigma_1 \) estimates for earthquakes in eastern and western Venezuela and on both sides of the Bocono fault (events 1, 3, 5, and 7) suggests that the small lateral displacement on the fault does not significantly affect our estimate of the Caribbean–South American convergence vector.

PRESENT-DAY SUBDUCTION OF THE CARIBBEAN BENEATH SOUTH AMERICA

Significant Cenozoic subduction of Caribbean oceanic lithosphere beneath South American continental lithosphere has been deduced from sedimentological [Duque-Caro, 1978] and gravity data [Case and MacDonald, 1973; Bonini et al., 1982]. Present-day subduction along the South Caribbean marginal fault (named in this paper) is indicated by folding and thrusting in the deformed belt and earthquake focal mechanisms and hypocenter locations.

The Colombian and Venezuelan basins are separated from the South American coast by a belt of deformed Tertiary and Quaternary sediments. Seismic reflection records from the Colombian Basin [Krause, 1971; Shepard, 1973; Case, 1974] and the Venezuelan Basin [Silver et al., 1975; Talwani et al., 1977; and Diebold et al., line 119, 1981] show that the belt of deformed sediments is being compressed, folded, and thrust to the north and west over Caribbean oceanic crust. Seismic line 129 (Figure 13) of the R. V. Conrad 2103 (J. B. Diebold, Lamont-Doherty Geological Observatory, Palisades, New York, unpublished data, 1979) crossed the South Caribbean marginal fault at the northwest margin of the deformed belt. The sediments appear to be overthrusting the oceanic crust to the northwest on a fault plane dipping 30° to the southeast. As a consequence of lateral compression and the high-pressure horizon in the deformed belt, mud volcanism and diapiric intrusion are presently active near Cartagena and northwest of Santa Marta [Shepard, 1973; Higgins and Saunders, 1974].

In Figure 12 earthquake hypocenters from Sykes and Ewing [1965] and Dewey [1972] have been projected onto a northwest-southeast cross section through the Perijas and the Santa Marta massif. The earthquakes occurred in a seismic zone dipping 30° to the southeast. The seismicity terminates 200 km below the Maracaibo Basin. The length of the Benioff zone is about 380–400 km. Sedimentary evidence suggests that subduction has moved from the Sinu trench in the last 10 m.y. [Duque-Caro, 1978]. If one assumes that the thickness of the lithosphere is 100 km, that the Benioff Zone started with an initial length equivalent to the rupture of the lithosphere 100 km/sin 30° = 200 km, and that the equilibration time for a cold slab is 10 m.y. [Isacks et al., 1968], then the subduction rate at the South Caribbean marginal fault is (390–200 km)/10² yr = 1.9 ± 0.3 cm/yr. This is very similar to the 2.2 ± 0.5 cm/yr Caribbean–South American convergence rate predicted by Minster and Jordan [1978].

The P wave derived fault plane solutions for events 1 and 2 in Figure 11 are consistent with subduction in a southeast dipping zone. Event 1 was produced by thrust faulting at a depth of 58 km below the deformed belt southeast of the South Caribbean marginal fault [Vierbuchen, 1978]. The nodal plane dipping shallowly to the
Fig. 13. Seismic line 129 of the R. V. Conrad 2103 (J. B. Diebold, Lamont-Doherty Geological Observatory, Palisades, New York, unpublished data, 1979). The sediments of the deformed belt appear to be overthrusting the sediments in the Colombian Basin on a fault plane dipping 30° to the southeast.
southeast coincides with the predicted zone of subduction. Event 2 was a deep earthquake (175 km) located southeast of the Perijas. The focal mechanism determination (O. Perez, W. McCann, and A. J. Murphy, Lamont-Doherty Geological Observatory, Palisades, New York, unpublished data, 1978) can be explained by east southeast down dip tension on the downgoing Caribbean lithosphere.

LOCATION OF PLATE MARGINS AND RELATIVE PLATE MOTIONS IN NORTHWESTERN SOUTH AMERICA

Estimates of the post-middle Eocene sinistral displacement on the Caribbean-North American plate boundary are as large as 1000 km. These estimates are based on the horizontal displacement of Mesozoic evaporites in Central America [Pinet, 1972] and the opening of the Cayman trough [Holcombe et al., 1973]. These estimates of Caribbean-North American movement can be combined with the constraints on relative motion between North America and South America derived by Minster et al. [1974] and Ladd [1976] to deduce the upper Tertiary Caribbean-South American motion as approximately 600-1000 km (1.5-2.2 cm/yr) (45 x 10^6 yr) in a west northwest-east southeast direction [Jordan, 1975; Minster and Jordan, 1978; K. Burke, Department of Geological Sciences, SUNY, Albany, New York, personal communication, 1980]. Upper Tertiary displacement of this magnitude did not take place on the Oca, Santa Marta, or Bocono fault systems. The upper Tertiary movement on the Oca and Santa Marta faults is the result of shortening in the Perijas and Santa Marta massif. This shortening is related to convergence at the South Caribbean marginal fault where significant Cenozoic subduction of Caribbean lithosphere beneath South America has been deduced from sedimentological [Duque-Caro, 1978] and gravity data [Case and MacDonald, 1973; Bonini et al., 1982].

The present Caribbean-South American plate boundary is the South Caribbean marginal fault that separates the Colombian and Venezuelan basins from the South Caribbean deformed belt (Figure 11). Present-day subduction of Caribbean oceanic lithosphere beneath South American continental lithosphere is indicated by folding and thrusting in the deformed belt and earthquake focal mechanisms and hypocenter locations. The seismic zone dips 30° to the southeast and terminates 200 km below the Maracaibo Basin (Figure 12). If one assumes that the thermal equilibration time for a cold slab is 10 m.y., then the subduction rate for the Colombian trench = 1.9 ± 0.3 cm/yr.

The late Cenozoic Caribbean-South American convergence has produced a northwest-southeast maximum principal stress direction σ1 in the overriding South American plate. Estimates of σ1 based on reverse fault P wave focal mechanisms for earthquakes in northwestern South America (Figure 11; Table 2) are 297°, 310°, 316°, and 317°. These values correspond well with our estimates of maximum compressive stress directions for the Sierra de Perija (299°), the Santa Marta massif (312°), and the Venezuelan Andes (320°) based on structural and gravity data.

The late Cenozoic uplifts and adjacent depressions of the Santa Marta massif, Perijas, and Venezuelan Andes were caused by over 100 km of crustal shortening and overthrusting to the northwest [Bonini et al., 1982]. The orientation and timing of this compression suggest that it is associated with the nonmagmatic subduction of Caribbean oceanic crust beneath South American continental crust. The Laramide Wyoming and Colorado Rocky Mountain uplifts [Grose, 1972] and the Andean uplifts of Peru [Dickinson and Snyder, 1978] have also been related to compressive stresses produced at a magmatic gap in a converging continental-oceanic plate boundary.

Present-day east northeast-west southwest compression is indicated by three earthquake focal mechanisms (Table 2) and is also suggested by Quaternary displacement and major historic earthquakes on the
Bocono fault. Compressive stress directions (Table 2) estimated from the focal mechanisms are very close to the east-west (080°) relative convergence vector for the Nazca and South American plates. The dextral strike slip motion on the Bocono fault (about 1 cm/yr for the last 10,000 yr) is probably intraplate deformation associated with Nazca-South American convergence. Greater seismicity is associated with the east-west Nazca-South American convergence than with the northwest-southeast Caribbean-South American convergence because the Nazca-South American relative velocity (7–8 cm/yr) is about 3 to 5 times greater than the Caribbean-South American relative velocity (1.5–2.8 cm/yr) [Jordan, 1975; Minster and Jordan, 1978].

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