J. E. CASE *U.S. Geological Survey, Corpus Christi, Texas 78411*
W. D. MACDONALD *State University of New York at Binghamton, Binghamton, New York 13901*

Regional Gravity Anomalies and Crustal Structure in Northern Colombia

ABSTRACT

The central range of the Colombian Andes gives way northward to a series of Cenozoic fault-bordered basins and uplifts near the Caribbean Sea. Pre-Cenozoic structures exposed in the uplifts curve increasingly toward the east to become parallel to the continental margins along the south side of the Caribbean. Major Cenozoic faults, with large vertical and horizontal displacements, cut across older structures which include Permian-Triassic(?) and Late Cretaceous to early Tertiary metamorphic zones, Precambrian gneiss, and Jurassic batholiths.

Gravity anomalies have large amplitudes in the Santa Marta area. Bouguer anomalies rise to +130 mgals over the crystalline rocks of the high Santa Marta massif. Over adjacent Cenozoic basins, they range down to −80 mgals over the Lower Magdalena basin and to −65 mgals over the Baja Guajira basin. Steep gravity gradients characterize the Santa Marta and Oca faults on the west and north sides of the massif, respectively.

In the Guajira Peninsula region, Bouguer anomalies increase to +105 mgals over a serpentinite zone at Cabo de la Vela and to +55 mgals over Cretaceous volcanic rocks in the southern peninsula. Two smaller basins on the peninsula are characterized by negative Bouguer anomalies. Steep gradients characterize many of the major Cenozoic faults, and two concealed faults are postulated on this basis.

Though useful for evaluating the relative vertical displacements, which may exceed 10 km along faults bounding the Santa Marta massif, the gravity data yield no definitive information on the large horizontal displacements postulated along some of the major faults of the area. The Bouguer anomalies do indicate, however, the extension of some of the Cenozoic basins into offshore areas.

Strong positive Bouguer anomalies of the Santa Marta massif and its great relief, which exceeds 9 km relative to the floor of the adjacent Caribbean, indicate thin continental crust, lack of isostatic balance, and relatively recent uplift for the massif. After corrections are made for the gravitational effects of Tertiary sedimentary basins in the Guajira Peninsula, most of the peninsular region also has positive anomalies, suggesting a relatively thin continental crust and a lack of isostatic balance. A mechanism of overthrusting, in relatively recent time, of the continental margin over the adjacent Caribbean upper mantle and crust to the northwest can account for the observations.

INTRODUCTION

In northern Colombia, the Andes change from a parallel and continuous linear mountain system to a disconnected series of irregular basins and uplifts. Structural trends in this area bend sharply from north-south into an east-west direction, becoming parallel to the southern margin of the Caribbean Sea. The pre-Tertiary geology of the region is known from the uplifts, such as the Santa Marta massif (Sierra Nevada de Santa Marta) and the several smaller ranges of the Guajira Peninsula (Fig. 1). The Tertiary history is preserved mainly in the sedimentary rocks of the intervening and adjacent basins.

The principal recent sources of geologic information on this area have been the mapping programs of the Colombian Instituto Nacional de Investigaciones Geológico-Mineras (INGEOMINAS), of Princeton University, and of the State University of New York at Binghamton. Complementing these geologic studies, regional gravity and magnetic surveys have been carried out in cooperation with INGEOMINAS and the Colombian Instituto Geográfico "Agustín Codazzi" (IGAC). These geophysical studies are part of a larger geophysical and tectonic investigation of northern

Geological Society of America Bulletin, v. 84, p. 2905–2916, 6 figs., September 1973

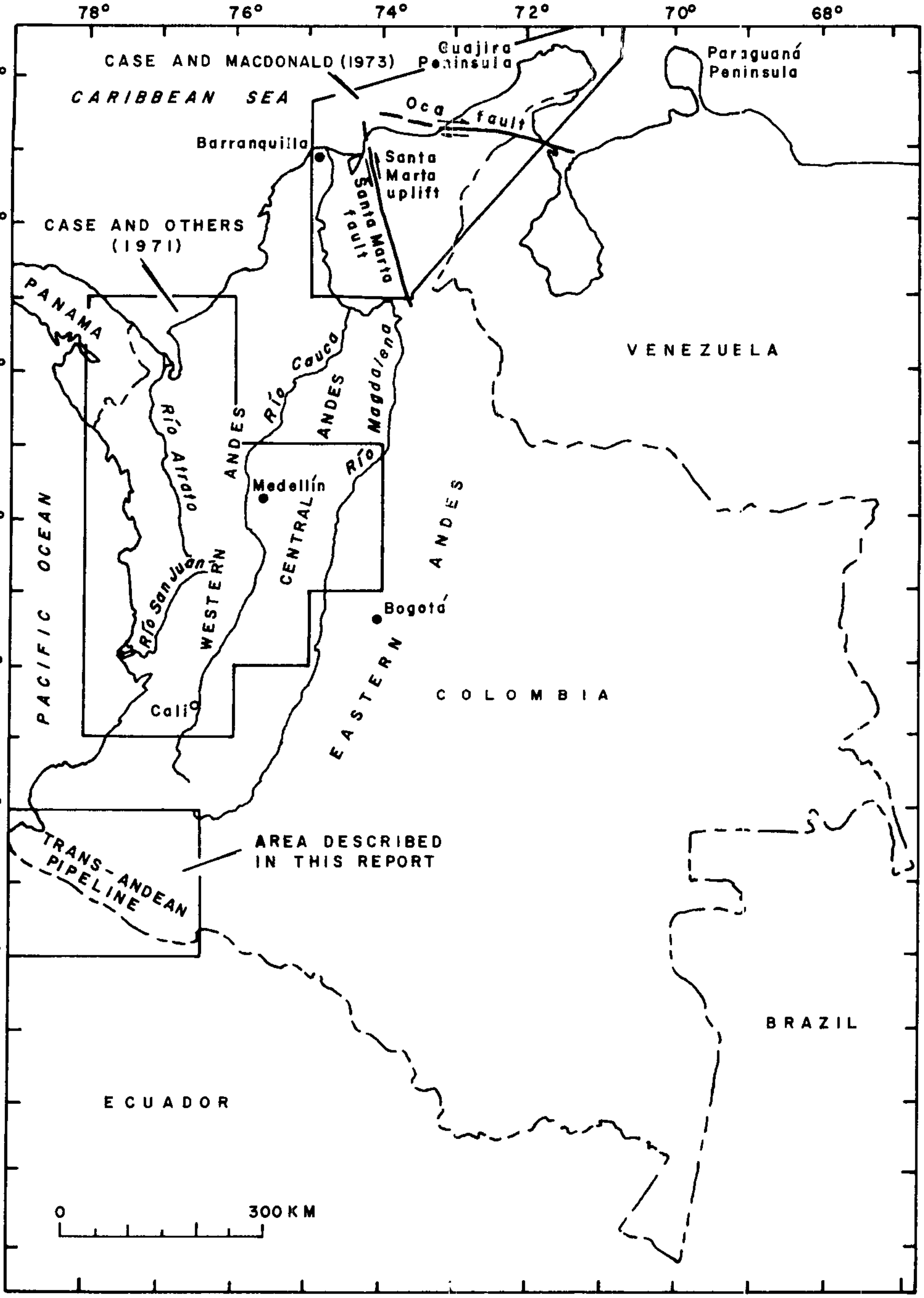


Figure 1. Index map of Colombia showing areas in which new gravity and magnetic surveys have been conducted. Location of the Santa Marta uplift and Guajira Peninsula indicated by dark outline.

South America and vicinity (Case and others, 1971, 1973). The present report summarizes our interpretations of the regional gravity survey.

SUMMARY OF REGIONAL STRUCTURE

Santa Marta Massif and Adjacent Basins

The Santa Marta massif is one of the most spectacular geologic features of Colombia (Fig. 2). Topographically, it is an isolated high, rising to glacier-capped peaks near 5,800 m elevation, surrounded by arid lowlands near sea level. In the Caribbean Sea 85 km to the north, water depths exceed 3,500 m, making the total topographic relief in excess of 9,000 m. Geologically, the massif resembles a gigantic horst surrounded by Cenozoic basins: the Lower Magdalena basin, the Cesar basin, and the Baja Guajira basin. The massif is bordered by the left-lateral Santa Marta fault on the west, and by the right-lateral Oca fault on the north. Each is believed to exceed 200 km in length and to have a large component of vertical displacement. The post-Cretaceous structural relief across the Santa Marta fault is thought to be as much as 12,000 m (Campbell, 1968) and may be 10,000 m across the Oca fault. The geology of the Santa Marta massif has been summarized by Tschanz and others (1969), and the distribution of the major rock units is shown in Figure 2.

The thickness of Tertiary strata in the adjacent basins has been estimated at more than 4,000 m for the Lower Magdalena basin (Irving, 1971), at more than 4,000 m for the Baja Guajira basin (Irving, 1971), and at least 2,000 m for the Cesar basin (Campbell, 1968, Fig. 7). In addition to the important vertical motions which have taken place along the border faults of some of these basins, controversial large strike-slip displacements have been postulated. The arguments have been summarized by C. M. Tschanz and others (1971–1972, written commun.), Campbell (1968), Polson and Henao (1968), and Feo-Codecido (1973). C. M. Tschanz and others (1973) conclude that as much as 65 km of right-lateral displacement of the metamorphic basement occurred on the Oca fault between Late Jurassic and Eocene(?) time and that up to 110 km of left-lateral displacement occurred on the Santa Marta fault between middle Cretaceous and Paleocene(?) time. Subsequently, large vertical displacement occurred on both faults since early Miocene time and up to one-third of the right-lateral displacement could be Eocene or younger. The offset on the Oca is somewhat larger than the post-Paleocene offset suggested by MacDonald and others (1971), who showed that the Oca fault cuts across the Ruma metamorphic zone of latest Cretaceous to Paleocene age. The post-Paleocene lateral offset on the Oca fault can be estimated from the offset of this zone. The apparent offset is no more than a few tens of kilometers. The critical area, from the point of view of demonstrating offset, is buried beneath the sediments of the Baja Guajira basin. The resolution of the movement on this, and on the Santa Marta fault, requires further mapping and age dating of the metamorphic rocks, more subsurface sampling, and detailed gravity and seismic surveys of adjacent offshore areas.

Guajira Peninsula

North of the Oca fault, an arid lowland, the Baja Guajira, is underlain by a large Tertiary basin, the axis of which is close to the Oca fault (Irving, 1971). To the northeast is an arid upland, the Guajira Peninsula, also called the Alta Guajira. Here, several small ranges (serranías) of pre-Tertiary rocks are interspersed with Tertiary basins (Fig. 3). Our present knowledge of the geology of this area is based on the studies of Bürgl (1960), Renz (1960), MacDonald (1964, 1968), Rollins (1965), Lockwood (1965, 1971), Alvarez (1967, 1971), Thomas (1972), and MacDonald and Opdyke (1972). The trends of the ranges and basins are controlled by Tertiary faults of dominant northwest trend, whereas within the pre-Tertiary rocks the structural trends are predominantly east-northeast.

The oldest rocks of the peninsula are exposed in an axial zone that trends east-northeast, the Guajira arch (Lockwood, 1965). This arch, now much segmented by Cenozoic faulting, contains metamorphic and igneous rocks of Precambrian to Permian(?) age. The oldest dated rock, the Jojoncito gneissic leucogranite (Fig. 3), has an age of about 1,250 m.y. (P. Banks, 1971, written commun.). Granulites similar to those in the Sierra Nevada massif, however, have not yet been found north of the Oca fault. An age of 195 m.y. (MacDonald, 1968) is regarded as a minimum age for the Permian-

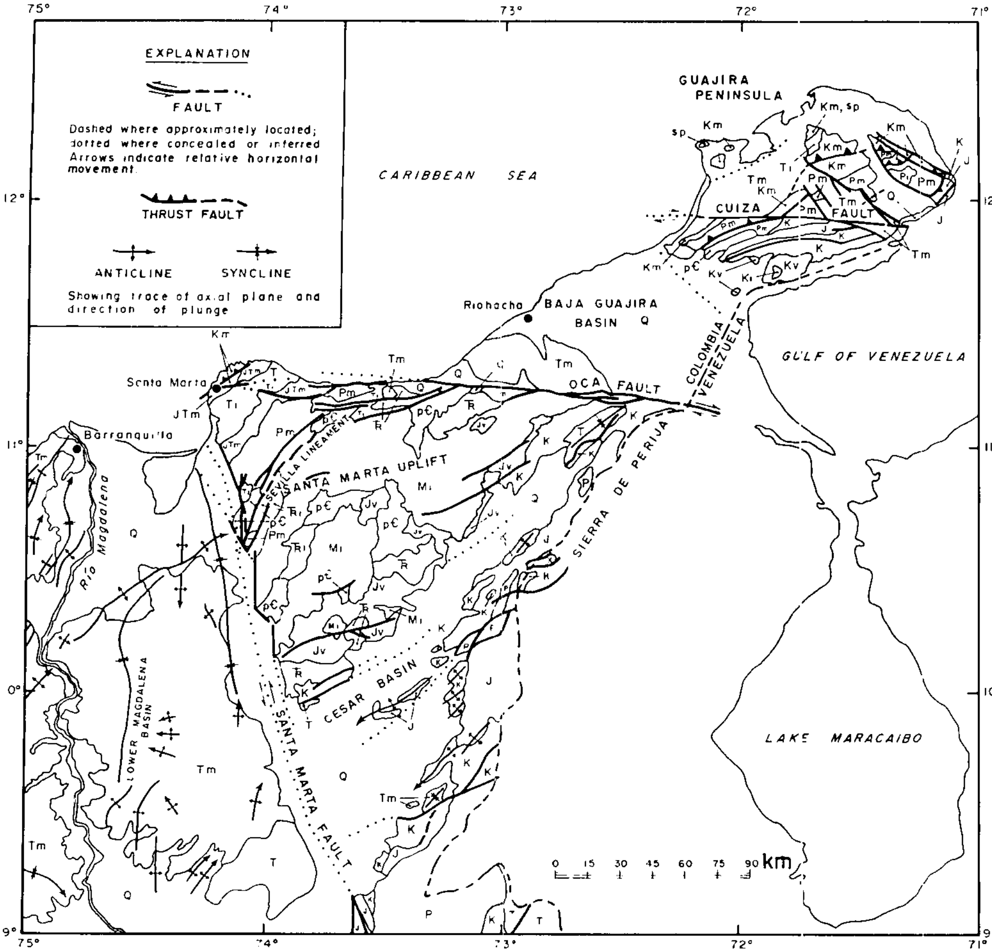


Figure 2. Generalized geologic map of the Santa Marta–Guajira areas, Colombia (modified from Irving, 1971; Tschanz and others, 1969; and C. M. Tschanz, R. R. Marvin, Jaime Cruz B., and others, unpub. data): p€, Precambrian metamorphic rocks of high grade; Pm, Paleozoic(?) metamorphic rocks of high grade, includes rocks metamorphosed during Permian, and Permian(?) metadiorite and related rocks; Pi, upper Paleozoic or lower Mesozoic syntectonic granitic intrusions; P, Paleozoic miogeosynclinal sedimentary deposits; Ŧ, Triassic marine and terrestrial (?) sedimentary rocks and volcanic rocks; Ŧi, syntectonic batholith of Triassic(?) to Jurassic age, granodioritic; Mi, Mesozoic, chiefly Jurassic, intrusive rocks, dioritic to quartz monzonitic, includes Early Cretaceous granitic plutons; Jv, Jurassic volcanic rocks; J, Jurassic miogeosynclinal and shelf deposits, locally includes volcanic rocks; Km, rocks metamorphosed during Cretaceous or early Tertiary, eugeosynclinal(?) in part; K, Cretaceous miogeosynclinal and shelf deposits; Ki, Cretaceous diorite; Kv, Cretaceous volcanic rocks; JTm, rocks possibly metamorphosed during Jurassic(?) but more likely in Cretaceous to Paleocene time; sp, serpentinite; Ti, Eocene quartz diorite plutons; Tm, Tertiary marine sedimentary rocks; T, Tertiary continental sedimentary rocks; Q, Quaternary alluvium.

Triassic deformation and metamorphism of the rocks of the arch.

Two distinct late Mesozoic tectonic provinces can be recognized south of the Guajira arch. Immediately adjacent to the arch are isoclinally folded Upper Jurassic and Cretaceous sedimentary rocks (Renz, 1960; Rollins, 1965; MacDonald, 1968) of the narrow Guajira trough. Southeast of this trough is the Cocinas platform, with flat-lying Cretaceous sedimentary rocks on a base of Lower Cretaceous felsic volcanic rocks and red beds (MacDonald and Opdyke, 1973). These are intruded by the Ipapure Diorite, also of Cretaceous age.

Northwest of the Guajira arch, the Cretaceous rocks change abruptly to Cretaceous metamorphic rocks of greenschist to amphibolite facies in the Ruma metamorphic zone. The original age of the greenschists has been demonstrated by several fossil assemblages, mostly of Late Cretaceous age. The schists contain numerous bodies of serpentinite, but metamorphosed basaltic rocks are scarce. Metamorphism took place in approximately Paleocene time and was followed by the intrusion of the Parashi Diorite of Eocene age (Fig. 3).

The oldest known Cenozoic rocks are Eocene sandy-marine limestones south of the Cocinetas basin and south of the Chichibacoa basin (Thomas, 1972). Oligocene limestones are extensively exposed around the margins of the Tertiary basins, but Miocene sandstones and shales form the greatest thickness of sediments in the basins.

Tectonic Summary

At least four major tectonic events of Permian and younger age can be recognized which are of importance in understanding the crustal history of this area. Two orogenic deformations resulted in the formation of metamorphic rocks, in Permian-Triassic and Late Cretaceous to early Tertiary time. A major episode of batholithic intrusion and rhyodacitic volcanism can be identified in Jurassic to middle Cretaceous time. The latest event is late Tertiary block faulting on a large scale, accompanying the Andean orogeny, which is more typically represented by folding, intrusion, and andesitic volcanism in the main Andean ranges farther south.

INTERPRETATION OF REGIONAL GRAVITY ANOMALIES

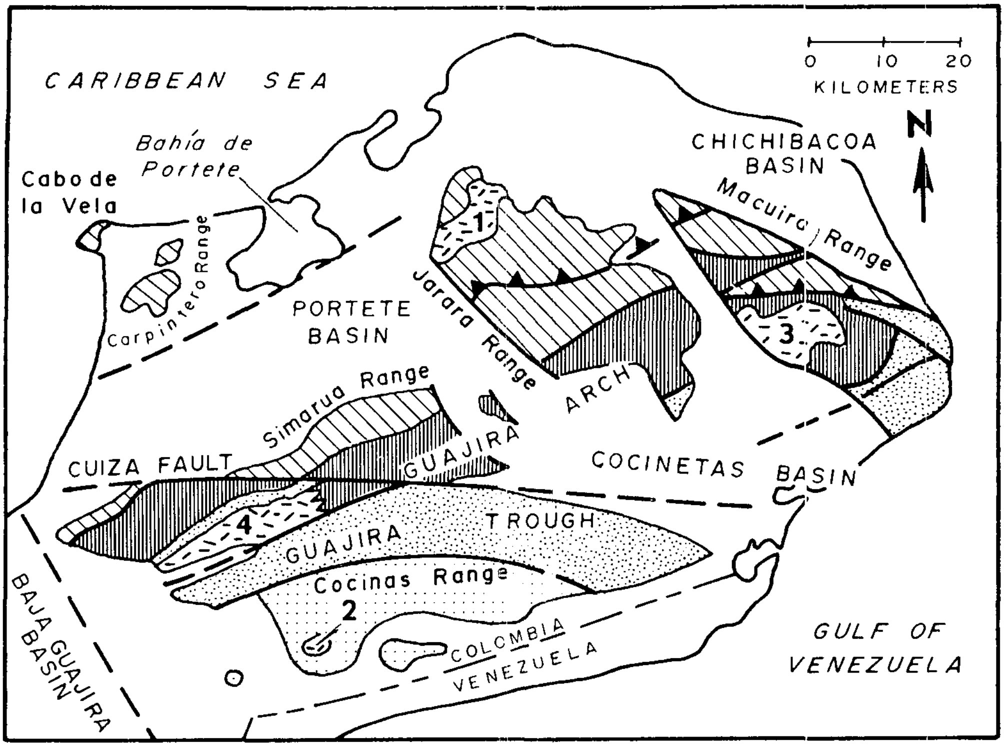
Bouguer anomalies have an enormous range in the region (Fig. 4). Large positive anomalies occur over the northwest Santa Marta massif, over Cabo de la Vela in the northwest Guajira Peninsula, and over the southern part of the peninsula. Negative anomalies are found over the Lower Magdalena and Baja Guajira basins. Smaller negative anomalies are associated with the smaller basins, the Cocinetas and Chichibacoa basins (Fig. 3), in the Guajira Peninsula. (A brief description of the gravity surveys is found in Appendix 1.)

A large negative anomaly with a south-plunging axis is caused by the thick sequence of low-density Tertiary sedimentary rocks in the Lower Magdalena basin (Fig. 4). Bouguer anomalies decrease from about zero near Barranquilla to -80 mgals at lat 10° N. Irving (1971) indicated a depth of 2,000 m of pre-Tertiary basement over much of this basin; seismic data suggest depths locally reaching 6,000 m. Sediments of the Magdalena delta are apparently now accumulating offshore well north of the thickest sequence of Tertiary deposits in the Lower Magdalena basin.

The eastern boundary of the Lower Magdalena basin gravity low is a very steep gravity gradient (Fig. 4) coinciding with the mapped trace of the Santa Marta fault zone (Fig. 2). Bouguer anomaly values increase rapidly eastward to more than $+100$ mgals across the fault. Gradients are as steep as 7 mgals per km between Ciénaga Grande and Santa Marta where the fault strikes into the Caribbean. Much of this gradient reflects the vertical displacement across the fault and the density contrast between the crystalline rocks of the uplift (density range estimated to be 2.7 to 3.0 g per cm^3) and the Tertiary sedimentary rocks (mean density estimated to be 2.4 g per cm^3 or less). The gravity data provide no critical information on the amount of strike-slip displacement along the Santa Marta fault. Detailed, closely spaced offshore gravity and seismic surveys along the northern trace of the fault would be of value in resolving this question of horizontal displacement.

Bouguer anomalies attain maximum values in excess of $+130$ mgals in the northwestern corner of the Santa Marta massif. If corrections for effects of local topography were made, the Bouguer anomalies would be even more positive. Such strongly positive values are due in part to relatively dense metamorphic rocks, but, more important, they indicate that the continental crust here must be relatively thin and that the area is out of isostatic equilibrium. Rocks of the extreme northwest part of the uplift may well have been formed from oceanic crust as proposed by Tschanz and others (1973).

To the northeast, a steep gravity gradient lies along the Oca fault (Fig. 2) and is the expression of the contrast in density between the crystalline rocks of the Santa Marta massif and sedimentary rocks of the Baja Guajira basin (Fig. 4). Here, again, the gravity data provide no information on the extent of strike-slip displacement along the Oca fault. The gravity anomaly over the Baja Guajira basin is quite asymmetrical; gradients are much



TECTONIC UNIT	ROCK UNIT
	CENOZIC MARINE SEDIMENTARY ROCKS
COCINAS PLATFORM	CRETACEOUS VOLCANIC AND SEDIMENTARY ROCKS
GUAJIRA TROUGH	UPPER JURASSIC AND CRETACEOUS STRONGLY FOLDED SEDIMENTARY ROCKS
RUMA METAMORPHIC ZONE	UPPER CRETACEOUS SCHIST, MINOR SERPENTINITE
GUAJIRA ARCH	PRECAMBRIAN TO PERMIAN-TRIASSIC SCHIST AND GNEISS
	FELSIC PLUTONS: 1. PARASHI; 2. IPAPURE; 3. SIAPANA; 4. JOJONCITO

Figure 3. Tectonic map of the Guajira Peninsula (in part after Rollins, 1965; MacDonald, 1964, 1968; MacDonald and Opdyke, 1972; Lockwood, 1965; Alvarez, 1967, 1971; and Thomas, 1972). Pre-Tertiary structural patterns generally trend east-northeast, whereas the northwest Tertiary faults mainly control the trend of the ranges and basins.

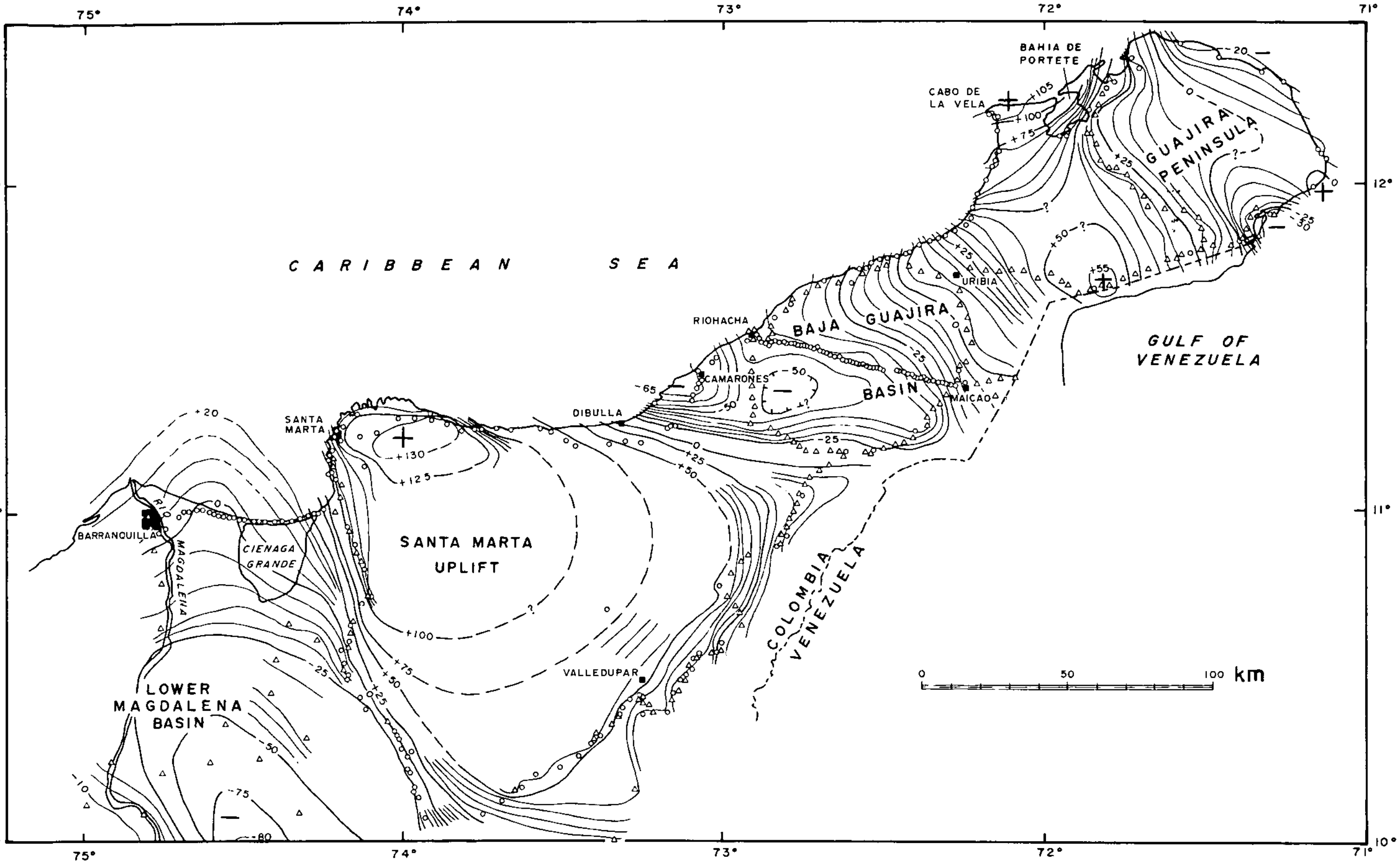


Figure 4. Simple Bouguer anomaly map of the Santa Marta–Guajira areas, Colombia. Contour interval 5 and 25 mgals. Reduction density = 2.67 g per cm³. Circles indicate stations established in 1971. Triangles indicate older stations established by IGAC. + indicates relative positive anomaly; — indicates relative negative anomaly.

steeper over the southern flank than the northern flank. This probably results from the asymmetry of the basin itself. The axis of the gravity minimum and, presumably, the thickest section of sedimentary deposits in this basin are along an east-west line just south of Camarones and Maicao. Reconnaissance gravity data offshore west of the Guajira Peninsula (C. O. Bowin, 1971, written commun.) indicate that the negative anomaly and the sedimentary basin extend at least 100 km to the west. In the same area, Krause (1971, Fig. 6, profile B-C) has shown on seismic profiles a basin containing more than 1,000 m of turbidites(?).

Gravity values increase uniformly from the axis of the negative anomaly northward toward the Guajira Peninsula. A steep gradient passing northwesterly through Uribia suggests that the Baja Guajira basin may be bordered by a northwest-trending concealed fault, as suggested by Lockwood (1965, Fig. 40). However, there is no surface expression of such a fault.

Gravity coverage in the Guajira Peninsula is scanty and is confined to lowland areas, and profiles across the various ranges are not available. Bouguer anomaly values range from −20 to +105 mgals, and most isogals trend northwest, parallel to the general trend of the later Cenozoic fault structures. However, a transverse trend and perhaps the most significant gravity anomaly of the Guajira Peninsula occurs over the Cabo de la Vela region, where Bouguer anomalies attain values as high as +105 mgals. Alvarez (1967, 1971) mapped exposures of serpentinite in this area, which may represent oceanic crust or upper-mantle material. Lockwood (1965; Green and others, 1968) discovered dense eclogitic boulders, associated with Mesozoic metamorphic rocks, in Tertiary conglomerate in the north-central peninsula. Unfortunately, the bedrock source of the boulders is unknown. The southeast flank of the positive gravity anomaly has a steep northeast-trending gradient, suggesting a major fault concealed beneath alluvial deposits. This fault, from surface geologic data, could be placed approximately along a line near the southeast side of Bahía de Portete (Fig. 3).

A positive vertical-intensity magnetic anomaly of about 1,400 gammas was also found over the serpentinite region of Cabo de la Vela. Krause (1971, p. 49) detected a large positive total-intensity anomaly of 400 gammas offshore to the southwest of Cabo de la Vela; this possibly represents an extension of the Cabo de la Vela anomaly. The offshore anomaly is traceable to about 11°50′ N., 72°45′ W. across the projected extension of the Cuiza fault (Fig. 2). If the correlation of magnetic anomalies is valid, it implies that the Cuiza fault has little strike displacement, that the fault changes trend to pass north or south of the magnetic anomaly detected by Krause, or that the source of the magnetic anomaly postdates the Cuiza fault.

A broad positive gravity anomaly extends over the south-central part of the Guajira Peninsula, culminating in a high of +55 mgals, just north of the Venezuela border (Fig. 4). This high overlies an area of Cretaceous (and possibly uppermost Jurassic) volcanic rocks. Because the Bouguer anomalies are strongly positive, continental crust in this area may be thin, or the area may have been nonisostatically uplifted.

From the available coverage, the Cuiza fault does not have a pronounced gravity expression, indicating that rocks on both sides of the fault have similar average densities. Although gravity coverage is incomplete, it is also interesting that the Guajira trough (Fig. 3), with its filling of thousands of meters of deformed Upper Jurassic and Cretaceous sedimentary rocks, has no significant expression in the gravity anomalies. This probably reflects low porosity of the limestone, sandstone, and shale resulting from extreme tectonic compression, so that they have mean densities close to those of the enclosing basement rocks.

A negative anomaly of about 30 mgals lies over the Cocinetas basin (Fig. 3). Rocks exposed in the vicinity of the basin are Eocene to Miocene in age. From the magnitude of the residual anomaly, these rocks probably exceed 2,000 m in thickness. The basin appears to be enlarging and plunging southeastward under the Gulf of Venezuela (Fig. 4).

A relative positive anomaly was found at the eastern end of the uplifted block of the Macuira Range (Fig. 3), reflecting the density contrast between the pre-Tertiary rocks of the uplift and the Tertiary sedimentary rocks of the adjacent basins.

Gravity values decrease seaward toward the northeast coast of the Guajira Peninsula. This suggests that a large sedimentary basin lies northeast of the Macuira Range and extends offshore. The landward portion of this, the Chichibacoa basin (Fig. 3), contains Eocene and younger, especially Miocene, strata

(Thomas, 1972). The size of the anomaly suggests that the thickness of these strata reaches several thousand meters. Reconnaissance data offshore (C. O. Bowin, 1971, written commun.) indicate a closed negative anomaly, the axis of which lies a short distance offshore with northwest trend parallel to the coast. A fault boundary farther northeast, southwest of the metamafic rocks of the Los Monjes Islands, can be anticipated. Bouguer anomalies near Los Monjes are strongly positive, over +44 mgals, so a residual anomaly of at least −60 mgal probably occurs over the basin.

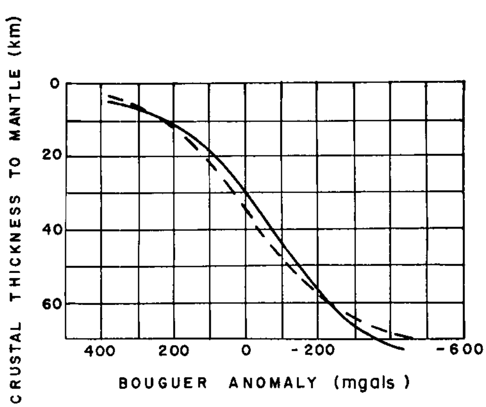


Figure 5. Crustal thickness versus Bouguer anomalies for areas largely in isostatic equilibrium. Modified from Demenitskaya and Belyaevsky (1969, Fig. 1), and Woollard and Strange (1962). Solid curve determined by Woollard and Strange, 1962; dashed curve determined by Demenitskaya.

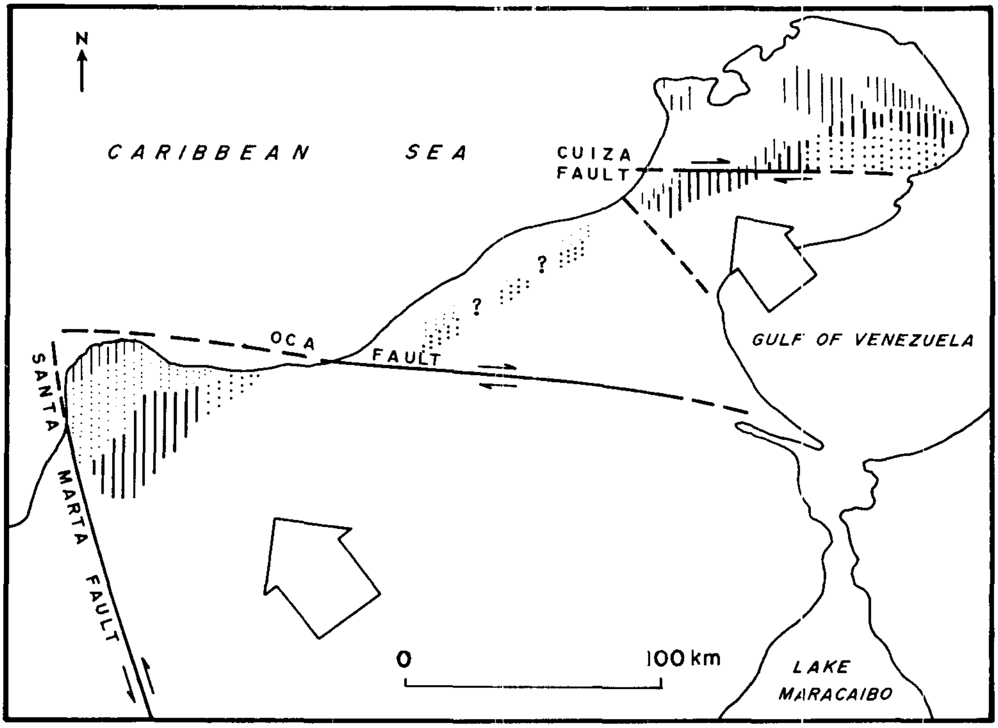
CRUSTAL IMPLICATIONS OF GRAVITY ANOMALIES

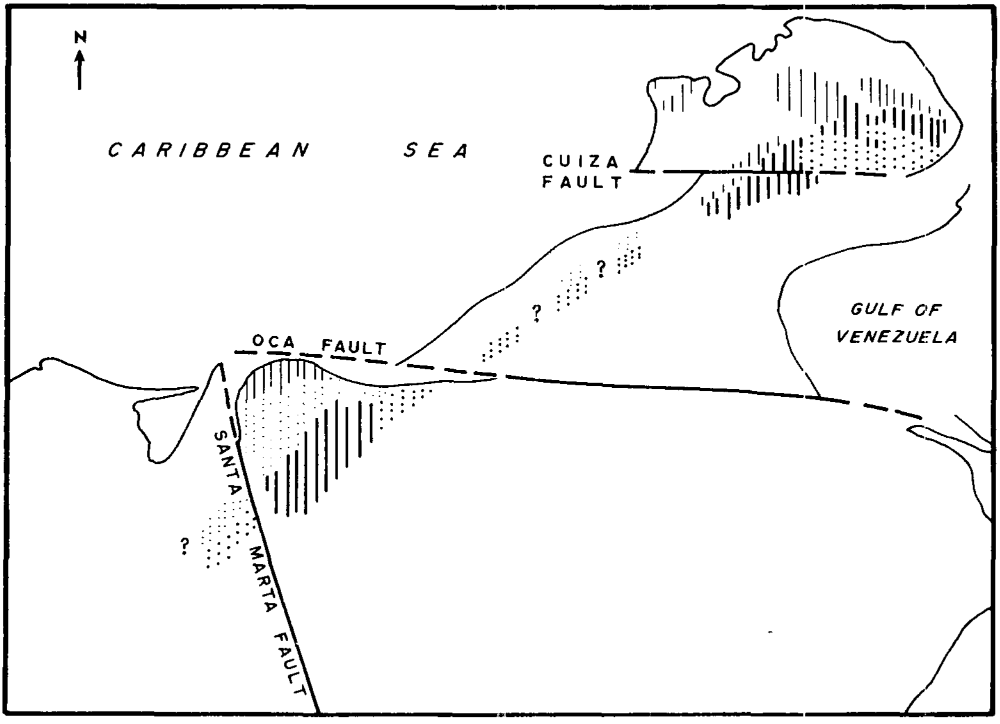
The regional gravity anomaly over the Santa Marta massif is essentially the opposite of what should be expected over a topographically high area of continental crust. For example, Woollard (1969, Fig. 6) has determined that in the northern Andes the mean Bouguer anomalies over 3° × 3° areas range from −50 mgals at 1,000 m elevation to −150 mgals at 2,000 m elevation. Clearly, the Santa Marta massif, rising above 5,000 m, with its Bouguer anomaly in excess of +100 mgals, is out of isostatic balance; an uncompensated excess mass must exist under the massif at relatively shallow depth. Empirical curves (Fig. 5) relating Bouguer anomalies to crustal thickness have been presented by Woollard and Strange (1962) and by Demenitskaya and Belyaevsky (1969). Their curves suggest that where mean Bouguer anomalies are about +100 mgals, the crustal thickness is on the order of 20 km, but these are oceanic regions where the crustal density is about 2.9 g per cm^3 (oceanic), rather than 2.67 g per cm^3 (continental) as used in the present calculations.

The anomaly over the uplift is still incompletely known, and it is difficult to isolate a residual anomaly over the uplift because of the gravitational effects of the deep adjacent sedimentary basins. If, however, the mean regional Bouguer anomaly field is assumed to be about zero near this continental margin, then the residual anomaly of the uplift is at least +130 mgals. We may further assume that the configuration of the uplift is represented by several superimposed right-circular disks: an upper disk having a thickness of 1 km, radius of 15 km, density contrast +0.1 g per cm^3, and top at 3 km above sea level; a middle disk having a thickness of 2 km, radius of 50 km, top at 2 km above sea level, density contrast +0.1 per g cm^3; and a lower disk having a thickness of 10 km, radius of 50 km, whose base is 10 km below sea level, and density contrast of +0.2 g per cm^3. The gravity anomaly at the top-center position for such a model is about 83 mgals. Obviously, if the assumptions and the suggested model above are correct, additional excess mass, either shallow or deep, is required to reproduce the residual anomaly of more than 100 mgals. The main point is that lower crustal or mantle material is abnormally close to the surface, and perhaps mantle material occurs at depths as shallow as 15 km below sea level. It is recognized that large density contrasts occur in the near-surface complex of granitic and metamorphic rocks that comprise the core of the uplift. For example, the range of densities may extend from 2.6 g per cm^3 of granitic bodies to 3.0 g per cm^3 over amphibolites and granulites. But, regardless of such near-surface contrasts in density, a large net excess of density must exist at the site of the uplift.

If corrections were applied to correct the gravitational effects of the Tertiary sedimentary basins on and adjacent to the Guajira Peninsula, much of that area would also be characterized by positive Bouguer anomalies. This implies a relatively thin continental crust and isostatic nonequilibrium under this area also.

The geologic history—from evidence of lithofacies, metamorphism, and plutonism—indicates that this area represents a continental


N
CARIBBEAN SEA
CUIZA FAULT
?
?
OCA FAULT
SANTA MARTA FAULT
GULF OF VENEZUELA
0
100 km
LAKE MARACAIBO


N
CARIBBEAN SEA
CUIZA FAULT
?
?
OCA FAULT
GULF OF VENEZUELA
SANTA MARTA FAULT
?

margin which has been repeatedly deformed. This is documented by the Jurassic batholiths and the Permian-Triassic and Late Cretaceous–early Tertiary metamorphic zones which are now exposed, some at high elevations. Great relief was formed on the surface of the pre-Tertiary crystalline rocks between the uplifts and adjacent Cenozoic basins during the late Tertiary Andean orogenic episode. To judge from the considerable thicknesses of Miocene sediments in the basins, the most recent episode of uplift is of middle Cenozoic or younger age. The strongly positive Bouguer anomalies suggest that the area has been placed out of isostatic balance relatively recently in the geologic past, perhaps as recently as Pliocene or Pleistocene time. Offset drainages and scarps indicate that some motion is still taking place.

A single mechanism can be proposed to account for both the great relief and the lack of isostatic balance of the Santa Marta massif. The explanation is that the continental crustal block of the massif has overridden the adjacent crust and upper mantle of the Caribbean, by a relatively recent overthrusting motion toward the northwest (Fig. 6). This mechanism has the possible advantage of also providing right-lateral motion on the Oca fault and left-lateral motion on the Santa Marta fault. A similar but smaller movement might account for the unusual positive Bouguer anomalies of the Guajira Peninsula, placing the crust of the peninsula slightly out of isostatic equilibrium.

This mechanism implies that the continental mass was the active element, overthrusting northwestward, but equivalent geometry and crustal relations result if the Caribbean plate was the active element, underthrusting southeastward.

Figure 6. Schematic mechanism of middle to late Cenozoic crustal movements. Upper diagram: present configuration, with Permian-Triassic(?) (heavy vertical lines) and late Cretaceous to early Tertiary (light vertical lines) zones of deformation and metamorphism shown. Arrows indicate directions of middle to late Cenozoic motion of continental crust, relative to Caribbean plate, as interpreted from motions on the Santa Marta, Oca, and Cuiza faults. These motions can also account for the relatively recent nonisostatic overriding of the continental crust over the Caribbean plate interpreted from Bouguer anomalies. Lower diagram: a reconstruction for early Tertiary time, based on aligning zones of metamorphism by reversing motions on faults. Dotted lines indicate suspected extent or former extent of metamorphic belts unknown because of subsequent intrusion, cover, or lack of radiometric dating.

ACKNOWLEDGMENTS

This research was partly supported by National Science Foundation Grant GA-19308 to the University of Missouri. The personnel of the InterAmerican Geodetic Survey, Panamá and Bogotá, provided outstanding support for this investigation. We have benefited from discussions and correspondence with many geologists who have worked in the region: C. M. Tschanz, E. M. Irving, J. P. Lockwood, Enrique Vásquez, Walter Alvarez, Barry Doolan, and David J. Thomas. Tschanz, Irving, Vásquez, Alvarez, C. O. Bowin, and D. J. Thomas supplied unpublished material. Andrés Jimeno V. and Jaime Cruz B. of INGEOMINAS arranged for logistical support, and José Quintero of IGAC provided access to unpublished geophysical data. Able field assistance was provided by Robert L. Bauer. Helpful review at various stages of preparation of this manuscript was provided by R. P. Morrison, C. O. Bowin, J. P. Lockwood, W. D. Gardner, C. M. Tschanz, Gabriel Dengo, and J. C. Maxwell.

APPENDIX 1. GRAVITY SURVEYS

Gravity data shown in Figure 4 have three sources: our surveys conducted in 1971, surveys established by the IGAC in the 1950s and 1960s, and data from the gravity anomaly map of Colombia (Instituto Geográfico "Agustín Codazzi," 1959). At all places where we obtained new stations at older sites, values of observed gravity agreed within 2 mgals of the older values, and these older values are regarded as quite acceptable for delineation of larger regional gravity anomalies. Because newer topographic base maps exist for much of the area, we were able to replot many of the old stations more accurately, and this required computation of new values of theoretical gravity because of corrected latitudes. At some places this meant changes in the Bouguer anomalies of 1 or 2 mgals.

Most of our new surveys were conducted by vehicle along the main highways and roads where elevation control was available. Unfortunately, access and elevation control are essentially nonexistent in the high interior of the Santa Marta massif so we obtained only a few stations at higher elevations. Surveys were conducted with La Coste & Romberg meter G-245. Stations were tied to reference stations of the IGAC–Inter American Geodetic Survey at the airports at Santa Marta, Riohacha, Maicao, and Valledupar. Most stations were established at benchmarks or along the coastline (where the tide range is less than 1 m), so that elevation control is excellent. Elevations for two stations in the interior of the massif were determined by altimetric loops; we estimate that these elevations are correct to within 20 m, equivalent to errors of 4 mgals in the simple Bouguer anomalies.

REFERENCES CITED

Alvarez, Walter, 1967, Geology of the Simarua and Carpintero areas, Guajira Peninsula, Colombia [Ph.D. dissert.]: Princeton Univ., 168 p.

—— 1971, Fragmented Andean belt of northern Colombia, *in* Donnelly, T. W., ed., Caribbean geophysical, tectonic, and petrologic studies: Geol. Soc. America Mem. 130, p. 77–96.

Bürgl, H., 1960, Geología de la Península de la Guajira, Colombia: Colombia, Bol. Geológico, v. 6, p. 129–168.

Campbell, C. J., 1968, The Santa Marta wrench fault of Colombia and its regional setting: Caribbean Geol. Conf., 4th, Port-of-Spain, Trinidad, 1965, Trans., p. 247–261.

Case, J. E., Durán S., L. G., López R., Alfonso, and Moore, W. R., 1971, Tectonic investigations in western Colombia and eastern Panamá: Geol. Soc. America Bull., v. 82, p. 2685–2712.

Case, J. E., Barnes, Jerry, Paris Q., Gabriel, González I., Humberto, and Viña, Alvaro, 1973, Trans-Andean geophysical profile, southern Colombia: Geol. Soc. America Bull. (in press).

Demenitskaya, R. M., and Belyaevsky, N. A., 1969, The relation between the Earth's crust, surface relief, and gravity field in the USSR, *in* Hart, P. J., ed., The Earth's crust and upper mantle: Am. Geophys. Union Geophys. Mon. 13, p. 312–319.

Feo-Codecido, Gustavo, 1973, Breves ideas sobre la estructura de la falla de Oca, Venezuela: Caribbean Geol. Conf., 6th, Margarita, Venezuela, 1971, Trans., p. 184–190.

Green, D. H., Lockwood, J. P., and Kiss, E., 1968. Eclogite and almandine-jadeite-quartz rock from the Guajira Peninsula, Colombia, South America: Am. Mineralogist, v. 53, p. 1320–1335.

Instituto Geográfico "Agustín Codazzi," 1959, Mapa gravimétrico, Republica de Colombia (Slinkard, R. M., principal compiler): Bogotá, Colombia, Inst. Geográfico "Agustín Codazzi."

Irving, E. M., 1971, La evolución estructural de los Andes más septentrionales, Colombia, S. A.: Bogotá, Colombia, Inst. Nac. Invest. Geológico-Mineras, 89 p.

Krause, Dale, 1971, Bathymetry, geomagnetism, and tectonics of the Caribbean Sea north of Colombia, *in* Donnelly, T. W., ed., Caribbean geophysical, tectonic, and petrologic studies: Geol. Soc. America Mem. 130, p. 35–54.

Lockwood, J. P., 1965, Geology of the Serranía de Jarara area, Guajira Peninsula, Colombia [Ph.D. dissert.]: Princeton Univ., 237 p.

—— 1971, Detrital serpentinite from the Guajira Peninsula, Colombia, *in* Donnelly, T. W., ed., Caribbean geophysical, tectonic, and petrologic studies: Geol. Soc. America Mem. 130, p. 55–75.

MacDonald, W. D., 1964, Geology of the Serranía de Macuira area, Guajira Peninsula, Colombia [Ph.D. dissert.]: Princeton Univ., 167 p.

—— 1968, Geology of the Serranía de Macuira area, Guajira Peninsula, northeast Colombia: Caribbean Geol. Conf., 4th, Port-of-Spain, Trinidad, 1965, Trans., p. 267–273.

MacDonald, W. D., and Opdyke, Neil D., 1972, Tectonic rotations suggested by paleomagnetic results from northern Colombia, South America: Jour. Geophys. Research, v. 77, p. 5720–5730.

MacDonald, W. D., Doolan, B. L., and Cordani, U. G., 1971, Cretaceous–early Tertiary metamorphic K-Ar age values from the south Caribbean: Geol. Soc. America Bull., v. 82, p. 1381–1388.

Polson, I. L., and Henao, Diego, 1968, The Santa Marta wrench fault; a rebuttal: Caribbean Geol. Conf., 4th, Port-of-Spain, Trinidad, 1965, Trans., p. 263–266.

Renz, O., 1960, Geología de la parte sureste de la Península de la Guajira (Republica de Colombia): Venezuela, Dir. Geol., Bol. Geol., Pub. Esp., no. 3, v. 1, p. 317–349.

Rollins, J. F., 1965, Stratigraphy and structure of the Guajira Peninsula, northwestern Venezuela and northeastern Colombia: Nebraska Univ. Studies, no. 30, 102 p.

Thomas, D. T., 1972, Tertiary geology and paleontology (phyllum Mollusca) of the Guajira Peninsula, Colombia [Ph.D. dissert.]: Binghamton, State Univ. New York, 150 p.

Tschanz, C. M., Jimeno V., Andrés, Cruz B., Jaime, and others, 1969, Mapa geológico reconocimiento de la Sierra Nevada de Santa Marta, Colombia: Bogotá, Colombia, Inst. Nac. Invest. Geológico-Mineras–U.S. Geol. Survey, scale 1:200,000.

Tschanz, C. M., Marvin, R. R., Cruz B., Jaime, Mehnert, Harald, and Cebula, G. T., 1973, The geologic evolution of the Sierra Nevada de Santa Marta, northeastern Colombia: Geol. Soc. America Bull. (in press).

Woollard, G. P., 1969, Regional variations in gravity, *in* Hart, P. J., ed., The Earth's crust and upper mantle: Am. Geophys. Union Geophys. Mon. 13, p. 320–341.

Woollard, G. P., and Strange, W. E., 1962, Gravity anomalies and crust of the Earth in the Pacific basin, *in* Macdonald, G. A., and Kuno, Hisashi, eds., The crust of the Pacific basin: Am. Geophys. Union Geophys. Mon. 6, p. 60–80.

MANUSCRIPT RECEIVED BY THE SOCIETY AUGUST 30, 1972

REVISED MANUSCRIPT RECEIVED FEBRUARY 2, 1973

PUBLICATION AUTHORIZED BY THE DIRECTOR, U.S. GEOLOGICAL SURVEY

PRINTED IN U.S.A.