INTERNATIONAL DECADE OF OCEAN EXPLORATION

U.S. GEOLOGICAL SURVEY

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REGIONAL GRAVITY ANOMALIES, VENEZUELA CONTINENTAL BORDERLAND

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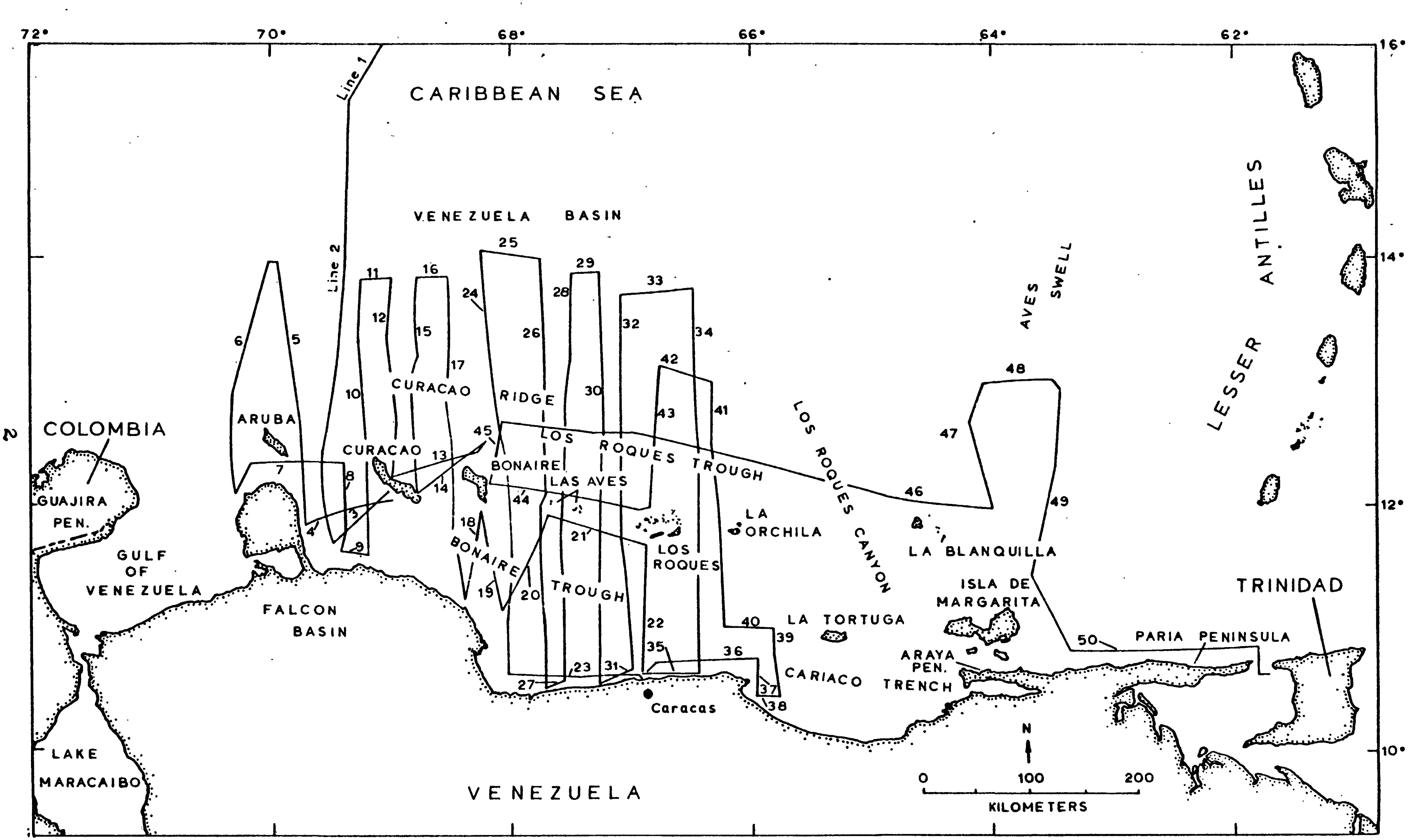

Figure 1. Index map showing locations of structural features and track lines in the continental borderland of Venezuela.

older pendulum data by Worzel (1965). Land gravity surveys have been conducted by Lagaay (1969) in the Netherlands Antilles and by Andrew and others (1970) in the Lesser Antilles. Much work has been conducted on land in Venezuela and Trinidad by petroleum companies, and some of the data have been presented by Folinsbee (1972). This preliminary discussion of new offshore gravity data was prepared by J. E. Case and Eli Silver.

Gravity data at sea were obtained with LaCoste and Romberg gravity meter S-53, which is a standard stabilized platform system. Land ties were made in San Juan, Puerto Rico; Willemstad, Curacao; La Guaira, Venezuela; and Port-of-Spain, Trinidad. From these ties, with both sea and land gravimeters, it appears that the value of observed gravity at the pendulum station in Willemstad, Curacao III, cited by Lagaay (1969, p. 9) is about 4.5 mgals too negative, and so the Curacao value was excluded from the computations of apparent drift of the sea gravimeter. Excluding the Curacao value, the apparent drift of S-53 with respect to observed gravity values in San Juan, La Guaira, and Port-of-Spain may be tabulated as follows:

		J.D.	Drift of S-53
San Juan	August 18	(230)	0.0 mgals
La Guaira	Sept, 16	(260)	-0.9 mgals
La Guaira	Sept. 24	(268)	+2.0 mgals
Port-of-Spain	Sept. 30	(274)	+0.2 mgals

Errors in observed gravity attributed to instrumental drift and to surge problems at dockside sites are negligible in comparison to problems at sea arising from errors in instantaneous values of Eotvos corrections caused by unknown course and speed between satellite and radar navigation fixes. This problem was particularly severe on Unitedgeo I whose automatic pilot malfunctioned at times, resulting in "fishtail" with a period of approximately one minute and course deviations of 20 degrees or more, equivalent to errors of up to 20 mgal in Eotvos corrections on some headings.

The only real internal test of errors in the gravity survey lies in the discrepancies of observed gravity (corrected for Eotvos effects) or free-air anomalies at the 27 points where lines crossed. These data are presented in histogram form in fig. 2. The crossing errors apparently ranged from 1 mgal to 16 mgals, with the mean error being 5.5 mgals. Many of the largest discrepancies occurred at points of steep gravity gradient, so that very small errors in true position may cause the apparent large crossing error.

Where free-air anomaly data from pendulum stations and adjoining shipborne surveys were plotted with data obtained on Unitedgeo I, the agreement was very good. In general, we can make a subjective estimate that the free-air anomalies of this survey along north-south lines are accurate to within 10 mgals. Accordingly, the free-air anomaly map (fig. 3) and a simple Bouguer anomaly map (fig. 4) have been contoured at an interval of 25 mgals. The simple Bouguer anomaly map is for a reduction density of 2.67 g per cm^3. Note that the section of the map from Peter (1971) is a "two-dimensional" Bouguer anomaly map. (In making simple Bouguer corrections at sea, the water beneath the station is replaced by an infinite slab of rock material. If the station is in an

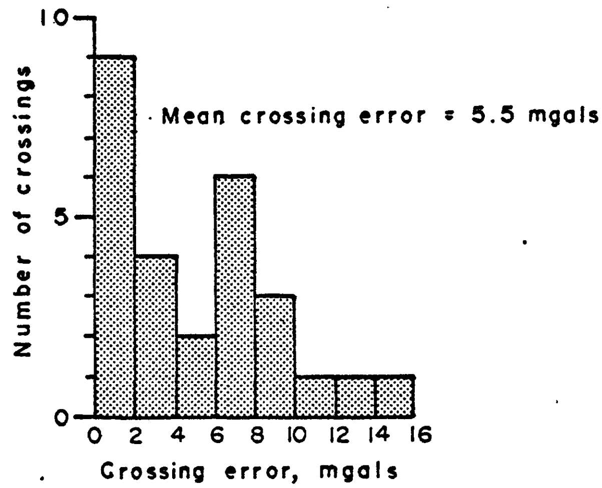

Figure 2. Histogram showing crossing errors in free-air anomalies, Venezuela continental borderland.

area of steep topography, the assumption of a horizontally-infinite water layer is, of course, erroneous. The two-dimensional correction partly takes account of topographic effects. As Peter (1971, p. 94-101) has pointed out, discrepancies of up to 40 mgals exist between simple Bouguer anomalies and "two-dimensional" Bouguer anomalies in the Venezuelan Borderland).

General Features of the Gravity Anomaly Maps

Gravity anomalies have an extremely large variation in the region, in keeping with the great variations in water depth and complex geology. Free-air anomalies range from more than -200 mgals over Los Roques Trench to more than +180 mgals on Bonaire (fig. 3; Lagaay, 1969, table 3). Simple Bouguer anomalies range from +340 mgals over the Venezuelan Basin to -50 mgals near the western end of Cariaco Trench (fig. 4).

Southward over the Venezuelan Basin, free-air anomalies range from 0 to -100 mgals and Bouguer anomalies from +340 to about +240 mgals, a typical range of values across margins of some ocean basins (Worzel, 1965). This regional southward decrease in values is partly the effect of a thickening wedge of sediments just north of the base of the continental slope. In the northwest part of the Venezuelan Basin, which has a relatively flat floor, isopachs of the sedimentary sequence from the surface of the seafloor down to seismic layer B" of Coniacian age (see Silver and others, 1972), indicate a basement structural or depositional high that trends northeasterly between latitudes 14°-16°N., longitudes, 67°-70°W. (fig. 5). Immediately south and southeast of the structural high, the total sedimentary section (Coniacian and younger) thickens from about 200 m on the crest of the high, near JOIDES drill site 150, to more than 4 km in the Venezuelan Basin, north of La Orchila (12°36'N., 66°19'W.). Turbidite-like reflectors appear south of the oceanic basement high province and thicken southward and eastward, as do the underlying older sediments.

The decrease in Bouguer anomaly values north of the base of the slope, however, cannot be attributed only to changes in sediment thickness. Neither can it be caused by changes in water depth (and hence in Bouguer corrections), as the depth range is less than 1000 m in the abyssal plain and depth changes are in the opposite direction to the changes in Bouguer anomaly values; that is, Bouguer anomalies are increasingly negative toward the extreme south edge of the Venezuelan Basin despite the fact that water depths are greater than in the basin to the north. Thus, part of the gradient must reflect a southward decrease in crust or upper mantle density or a southward increase in crustal thickness.

Deformed sedimentary rocks, presumably of Coniacian and younger age, comprise the broad region of the continental slope between the Netherlands-Venezuelan Antilles, from Aruba to La Orchilla, and the Venezuelan Basin. This belt includes the deformed outer Curacao Ridge, a terrace-like feature of very complex internal folding. To the south, Curacao Ridge extends as a topographic and structural high from the western edge of the surveyed area to Los Roques Canyon. Farther south, a major topographic and structural depression is found along Los Roques Trench. Locally, Los Roques Trench is filled with thick turbidite-like beds, some of which may be continuous with those to the north in the Venezuela Basin. This structural belt widens westward, narrows eastward, and essentially disappears at the south end of Aves Ridge, just northeast of La Blanquilla.

Outer Curacao Ridge and the main Curacao Ridge have associated relative positive free-air anomalies, although values are still negative. These local highs are almost certainly due in part to topographic effects, as is the local Bouguer anomaly high along lines 10, 12, and 15 (near lat 13°10'N.) which occurs over a topographic low.

One of the most significant regional anomalies is the great low over Los Roques trench where free-air anomalies are more negative than -200 mgals. Part of this low is a topographic effect; water depths range from 4600-5000 m in Los Roques trench--similar to depths in the Venezuelan Basin, but the anomalies over the trench are at least 100 mgals more negative than those over the Venezuelan Basin. A regional negative Bouguer anomaly, where values range from 60 mgals to 120 mgals, runs near the trench. A residual negative anomaly overlies Curacao Ridge north of Curacao and Bonaire. These regional gravimetric relations indicate that the thick wedge of deformed sediments extends from Curacao Ridge beneath Los Roques trench. Refraction data of Edgar and others (1971) indicate that at least 5 km of low-velocity material underlies Los Roques trench and up to 14 km of low-velocity material underlies Curacao Ridge.

From our seismic evidence on lines 26 through 41 it appears that flat-lying sediments of the Venezuelan basin become folded and incorporated in the deformed outer slope, and, from the truncation of isopachs at the toe of the slope, either massive down slope movement has occurred along the outer slope since Late Cretaceous time, or, more likely, the thick sequence of sediment has been progressively incorporated tectonically into the wedge of sediments now forming the Curacao Ridge complex. Where the Curacao Ridge Province is widest, sediments in the Venezuelan Basin at the foot of the continental slope are thinnest (near lines 2, 10, 12, and 15). Where Curacao Ridge is narrowest, north of La Orchila (near lines 34 and 41), the greatest thickness of relatively undeformed sediments is preserved. These relationships are consistent with the interpretation of a history of an apparent southeastward component of relative downward movement of the Caribbean basin with attendant folding and scraping off of the sedimentary sequence; the rate, duration or intensity of deformation may have been greater in the western part of the area than in the eastern part because of the greater degree of deformation to the west.

The line of islands extending from Los Monjes to Los Hermanos is a series of horst-like uplifts, forming topographic and structural highlands, generally bordered on their north sides by a marked zone of steep topographic slope, apparently complexly faulted. The zone of steepened topography is offset by cross faults between Aruba and Curacao, between Curacao and Bonaire, and between La Orchila and La Blanquilla.

The basement rocks are Late Cretaceous where dated by paleontologic or radiometric means and are composed of pillow basalts, diabase, tuff, chert, and flysch-type sedimentary rocks (see summaries by Lagaay, 1969, p. 34-40; Beets, 1971). The basement rocks of Aruba, Los Roques and La Orchila are greenschist facies assemblages, and those on Curacao are zeolite or prehnite-pumpellyite facies. The rock sequence on many of the islands was intruded by dioritic or quartz dioritic masses in Late Cretaceous time, and ignimbrites were erupted on Bonaire during this time (Beets and Lodder, 1967). A rich fossil-bearing chert horizon was discovered on Bonaire by some of the scientific staff of Leg 4. Ammonites from these beds are Late Cretaceous, probably Coniacian, in age (according to W. A. Cobban, written communication, 1971). The islands are capped with lagoonal limestone terrace deposits of middle to Late Cenozoic age.

From southeastern Aves Ridge, Nagle (in press) has reported dredge hauls of unfoliated metavolcanic greenschist facies rocks, basalt, volcanic conglomerate, and tuffaceous limestone. From farther north, he reported volcanic conglomerate and breccia, andesite, basalt, with minor dacite, tuff, and limestone. From Southern Aves Ridge, Fox and others (1971) reported granodiorite, diabase, porphyritic basalt, and metamorphosed basalt. Radiometric ages of the igneous samples indicate that they are no older than middle Cretaceous and no younger than Paleocene. Eocene to Miocene limestones were dredged at several localities between 12°30'-13°34'N. and 62°57'-63°32'W. From the broadly similar age ranges and lithologies of the basement rocks, the Leeward Antilles from Los Monjes to La Blanquilla are a structural continuation of Aves Ridge. This concept is reinforced by the patterns of regional free-air, Bouguer, and isostatic anomalies (fig. 6), as discussed below.

The regional southward decrease in free-air and Bouguer anomaly values is interrupted by a series of strongly positive values over the islands from Aruba to La Blanquilla. The coincidence of free-air and Bouguer anomalies as great as +75 to +180 mgals over Aruba, Curacao, and Bonaire with a suite of basement rocks having oceanic afinities

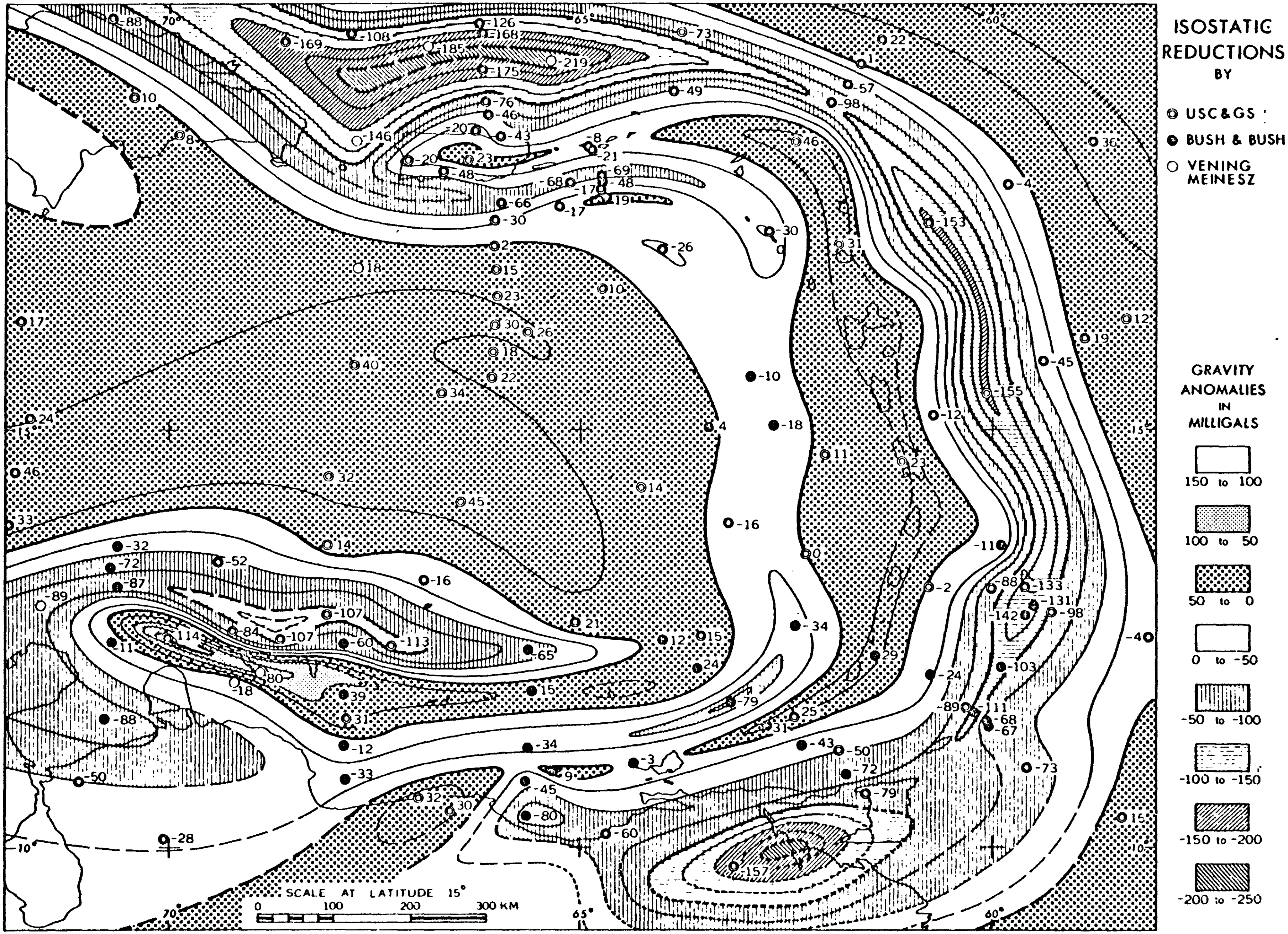

Figure 6. Pratt-Hayford isostatic gravity map of the Antilles Islands and Venezuelan Basin (Bush and Bush, 1969).

(pillow basalt, chert, and other marine sediments), indicates that these islands are raised blocks of dense, possibly oceanic crust. Similar anomalies over Las Aves, Los Roques, La Orchila, La Blanquilla-Los Hermanos, and the gravity high detected by Peter (1971) between La Blanquilla and Los Roques Canyon indicates that the basement framework comprises raised blocks of dense crust, intruded by granodiorite and quartz diorite. The total structural relief of Late Cretaceous crust, between Curacao and the base of seismic layer B", where it is 4 sec. (4 km, ca.) below the sea floor at the base of the continental slope (seismic line 41), is about 9 km. According to Peter, 1971, p. 152-153: "The positive free-air anomaly belt of the Aves Ridge extends into the Blanquilla platform where it joins the positive values associated with the Tortuga-Margarita Bank (Talwani, 1966). West of the Blanquilla platform the large negative free-air anomaly values of the Los Roques Canyon interrupt this belt, but west of the canyon the same belt appears to follow the islands of the Aruba-Orchila chain (Talwani, 1966; Lagaay, 1969)". This zone is also one of positive isostatic anomalies that extends from Aves Ridge to the Guajira Peninsula and beyond (Bush and Bush, 1969; Case and MacDonald, in prep.; fig. 6).

The group of positive anomalies over the islands is broadly aligned and extends from Los Monjes, on the west, to Aves Ridge on the east, but both free-air and Bouguer anomaly contours indicate that many of these high standing basement blocks are not directly connected and are probably separated by a series of northwest-trending, en echelon basement faults.

Major free-air and Bouguer anomaly minima between Aruba and Curacao indicate that this area is filled with a great thickness of sedimentary rocks, connecting the sedimentary wedge of Bonaire Basin with that of Los Roques Trench-Curacao Ridge. Steepened gravity gradients and seismic data indicate a major fault zone along the southwest margin of Curacao, close to the island shore. Similarly, steep gradients along the northeast coast of Aruba suggests a fault margin. Thus, the sedimentary basin may occur in a graben-like structural setting between the islands. These faults trend northwest and are approximately in the position inferred by MacDonald and others (1971, fig. 1) between Aruba and Curacao to account for the contrast in metamorphic grade between the islands.

Other zones of steepened northwest-trending free-air gravity gradients appear along the southwest flank of Aruba, southwest flank of Bonaire, between Las Aves and Los Roques, on both flanks of Los Roques Canyon, and southwest of La Blanquilla. These steepened gradients coincide with northwest-trending steep topographic gradients and in part simply reflect the topographic grain. However, the steepened northwest-trending gradients remain on the Bouguer anomaly map along the flanks of Aruba and Bonaire, along the northeast flank of Los Roques Canyon and the area southwest of La Blanquilla, so that real lithologic contrasts or structural zones are indicated. Peter (1971, fig. 38, p. 121-122, p. 133-136), for example, has presented seismic evidence for northwest-trending graben-like fault troughs in Los Roques Canyon. Los Roques Canyon may be underlain by a considerable thickness of sedimentary rocks judged from the negative free-air and residual negative Bouguer anomalies.

George Peter (written communication, 1972) suggests, however, that the gravity low indicates a graben that cuts the entire crust.

The sense of displacement along these transverse fault zones is difficult to determine. Most of the faults clearly have a large vertical component of displacement from both seismic and gravitational evidence. If one attempts to align the islands and their submarine extensions by restoration along strike-slip faults, a series of left-lateral displacements would be required on a system of northwest-trending faults. Galavis and Louder (1970, fig. 1A) inferred left-lateral displacement on the fault along the southwest margin of Aruba. In an analysis of the regional isostatic anomaly field, Lagaay (1969, fig. 13, p. 44, 75) noted offsets in the field in the vicinity of the Netherlands Antilles. These offsets could be fitted by a system of north-to northwest-trending right lateral faults (between Aruba and Curacao) or by a system of north-to northeast-trending left lateral faults (between Curacao and Bonaire). Despite such hints of strike-slip displacements, the general pattern seems to be one of an elongate block of uplifted oceanic crust that was pulled apart by east-west extension creating rifted zones between the blocks.

South of the Aruba-La Orchila highland is a major sedimentary basin, the Bonaire Basin, containing many complex folds. This basin is generally on trend with the folded Falcon Basin of the mainland. The basin evidently splits toward the west; a prong of thick sediments trends northwest between Curacao and Aruba and merges with the main basin extending west from Los Roques trench. A moderately thick sequence of basin sediments is preserved between Aruba and the Paraguana Peninsuia.

The peninsula has a basement of early Tertiary and older crystalline rocks. Isopachs of Feo-Codecido (1971) indicate at least 1500 m of Miocene sedimentary rocks at the north edge of the peninsula, and the attitudes of deep reflectors on lines 2 and 5 suggest that as much as 2000 m of sediments may be present.

Fold axes in the basins between the Netherlands Antilles and the mainland apparently trend west-northwesterly if our correlations between seismic lines are correct. In contrast, fold axes in the Falcon Basin tend to trend northeast. The sedimentary sequence in the Falcon Basin exceeds 4000 m (Vasquez, 1971, figs. 11, 12); the Oligocene and Miocene section is especially thick and consists of shale sequences along the edge of the mainland. A great total thickness of deformed Tertiary sediments probably extends from the Paraguana Peninsula eastward to La Orchila. Galavis and Louder (1970), for example, indicate that the basement is on the order of 5,000 m (3,000-4,000 m below the sea floor) below sea level in the Bonaire Basin.

A broad regional free-air gravity low is present over Bonaire Basin. Although the general configuration of the low parallels the topography, in detail the axis of the low is offset south of the main basin axis. Bouguer anomaly contours across the basin show a general southward decrease. Hence, it seems clear that deeper crustal density changes are partly masking effects of the topographic trough and sedimentary basin. Bouguer anomalies are strongly negative south of the mainland border, near Caracas, indicating that typical continental crust is developed at depth (Folinsbee, 1972, fig. 9).

A general gravity low or area of flattened gravity gradient extends eastward from the main Bonaire Basin to Grenada Trough, a sedimentary basin, between Aves Ridge and the Windward Antilles. In a broad regional sense these sedimentary basins are on trend although apparently interrupted by a cross structural high, structural saddle, or cross faults between Margarita-La Tortuga and La Orchila-Blanquilla according to Peter's (1971) gravity and seismic data. A regional negative isostatic anomaly extends from Grenada trough across the Bonaire Basin to the Falcon Basin (Bush and Bush, 1969, fig. 6).

One of the most significant regional gravity anomalies along the Caribbean margin is the pronounced gravity high that extends from the volcanic windward Antilles (Andrews and others, 1970; Bush and Bush, 1969) through Los Testigos (Lattimore and others, 1971) to Margarita. This positive anomaly, shown on free-air, Bouguer, and isostatic maps, extends westward through La Tortuga and was traced on our surveys to about 10°45'N., 67°W. The anomaly overlies metamorphosed Cretaceous and older(?) rocks on Margarita and seems to be caused by a raised complex ridge of basement rocks. Its continuity from the Tertiary volcanic Antilles to the Mesozoic basement complex of the Venezuelan borderland is doubly significant; first, the western part is related to a raised block of pre-Tertiary rocks. This suggests that the basement beneath the outer Antillean volcanic arc may be composed of dense pre-Tertiary crystalline rocks. Fink (1972) has reported Jurassic basement rocks on Desirade, where trondjemites intrude spilitic basalts which have interbedded cherts. Rocks analogous to the Tortuga-Margarita sequence probably serve as the deep foundation for the volcanic Antilles. Second, the near-continuity of this anomaly, even though the axis is offset somewhat between Margarita and Tortuga, precludes a "South Caribbean fault" having substantial post-Mesozoic strike-slip displacement between Margarita and Grenada, as pointed out by Peter and Lattimore (1971), Meyerhoff and Meyerhoff (1972, p. 51-53) and Weeks and others (1971, p. 1750-1751).

A major system of strike slip faults is present, however, along the Venezuelan Borderland; it lies along the Oca-San Sebastian-El Pilar system at the southern margin of the area. The large regional gravity gradient across the Cariaco Trench and Gulf of Paria indicates that the San Sebastian-El Pilar system is a major structural discontinuity with relatively dense crustal rocks to the north and relatively light or thick crustal rocks to the south. The gravitational and lithologic relations are similar to those across the Dolores megashear system in western Colombia (Case and others, 1971), which has been proposed as the boundary between dominant oceanic crust to the west and continental crust to the east.

Several prominent positive anomalies are found along line 50, which parallels and lies just north of the Paria Peninsula. Gonzalez de Juana and Munoz (1971) have mapped numerous bodies of pyroxene peridotite along the peninsula. One of the largest is located at Cabo Tres Puentas, immediately south of the largest positive anomaly along line 50 where free-air anomalies exceed +50 mgals and the Bouguer anomaly value is almost +75 mgals. It would appear that this ultramafic complex extends northward offshore to our line 50.

Regional Crustal Relations

A fundamental regional tectonic problem is the location of the northern margin of the Paleozoic and older craton of northern South America. Is there an abrupt or transitional boundary between continental "granitic" crust and oceanic "basaltic" Caribbean crust? Seismically, a transition zone evidently lies beneath the Venezuelan Borderland (Edgar and others, 1971, p. 838, fig. 22). Seismic data on crustal properties are relatively complete in the Caribbean but are nearly non-existent on the Venezuelan mainland.

In their comprehensive study of the gravity field of the Venezuelan Andes and adjacent basins, Hospers and Van Wijnen (1959) assumed a crustal thickness of 30 km both north and south of the Merida Andes, southwest of the area described in this report, where Bouguer anomalies range between 0 and -150 mgals, "continental" values. They assumed a mean density of 2.67 g per cm^3 and an upper mantle density of 3.27. The crust was inferred to thicken southward across the Maracaibo Basin, to a thickness of 40 km beneath the northwestern Merida Andes and then to thin abruptly to 30 km beneath the southern Merida Andes. Farther south, the crust thickens again to about 34 km beneath the Barinas-Apure Basin.

Lagaay's model across the Netherlands Antilles (1969, fig. 14; shows a gradual crustal thickening, from about a depth of 17 km in the Venezuelan Basin, to 24 km under Curacao Ridge, a slight upward bulge under Curacao, and thickening to 30 km at Venezuela. In his analysis of the isostatic anomaly profile, a mean crustal density of 2.67 g per cm^3

was assumed. In view of the seismic evidence of Edgar and others (1971) that the crust is dense and heterogeneous, having seismic velocities of 6.3 to 7.6 km/sec (densities 2.8 to 3.3 g per cm^3), we feel that his (Lagaay's) model is oversimplified.

Hambleton (cited by Worzel, 1965) constructed a crustal model across the Venezuelan borderland along longitude 68°W., based on free-air anomalies and seismic information (fig. 7). In this model the crust extends to depths of 16 km beneath the Venezuelan Basin, thins to 12 km near the base of the continental slope, thickens to about 16 km beneath Curacao Ridge, thickens to about 34 km between Bonaire and Las Aves, thins to 16 km beneath Bonaire Trench and thickens to 25 km at the Venezuelan margin. About 14 km of low-density (2.1-2.4 g per cm^3) material underlies Curacao Ridge, and shallow dense rocks (2.85 g per cm^3) lie within 2 km of the surface between Bonaire and Aves Passage. A mantle density of 3.4 g per cm^3 and a lower crustal density of 3.0 g per cm^3 were assumed. Perhaps the most conspicuous thing about Hambleton's model is that relatively dense rocks closely approach the surface near Las Aves and the total crust is much thicker beneath Las Aves than to the north beneath Los Roques Trench and to the south near Bonaire Basin.

Among other possibilities, the thickened and relatively dense crust beneath the Netherlands-Venezuelan Antilles could be associated with formation of a constructional island arc on a basement of older crust, or by multiple stacking of typical oceanic crust in a zone of convergence between an early Caribbean plate and nuclear South America. A more complete analysis of this question is being prepared for future publication.

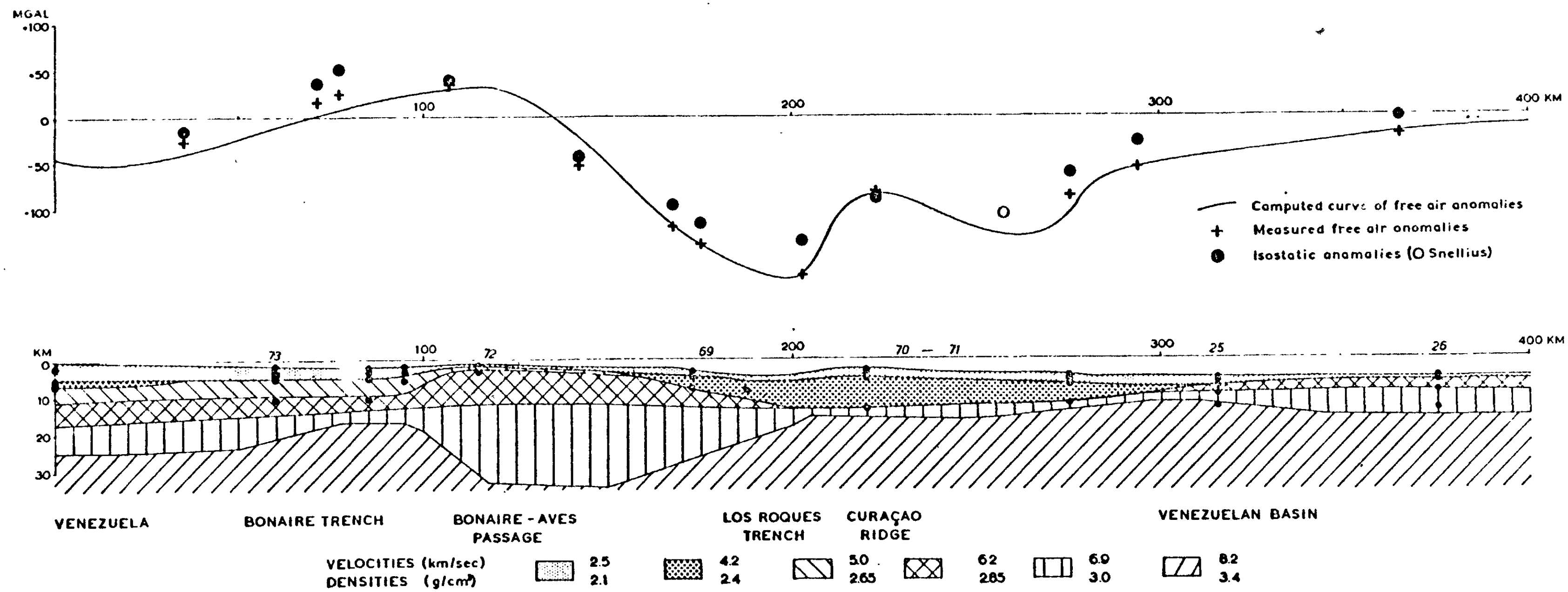

Figure 7. Crustal section at 68° W., constructed by Hambleton (Worzel, 1965) from free-air anomalies and seismic information.

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FIGURE 3-- FREE-AIR ANOMALY MAP, VENEZUELAN BORDERLAND

U.S. Geological Survey, I.D.O.E., 1971, Leg 4

FIGURE 4-- SIMPLE BOUGUER ANOMALY MAP, VENEZUELAN BORDERLAND
U.S. Geological Survey, I.D.O.E., 1971, Leg 4

FIGURE 5-- SIMPLIFIED TECTONIC MAP, VENEZUELAN BORDERLAND

U.S. Geological Survey, I.D.O.E., 1971, Leg 4

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