THE GRAVITY FIELD OF THE VENEZUELAN ANDES AND ADJACENT BASINS

BY

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PREFACE

The authors wish to thank Cia. Shell de Venezuela for permission to prepare and to publish this paper. They also wish to thank their colleagues whose help and advice are greatly appreciated.

Chapters II–VI, X and XI are the result of close collaboration between the authors. The remaining chapters (I, VII–IX) have been written by the first author.

I. GEOLOGICAL INTRODUCTION

a. *Morphological and structural provinces of northwestern South America*

Northwestern South America, comprising the whole or parts of the countries of Brazil, Colombia, Ecuador, Peru, and Venezuela, can be divided into a number of distinct morphological and structural provinces (Fig. I – 1), following LIDDLE (1928), STAFF etc. (1948), BUCHER (1952), YOUNG *et al.* (1956), and H. J. HARRINGTON (in JENKS, 1956).

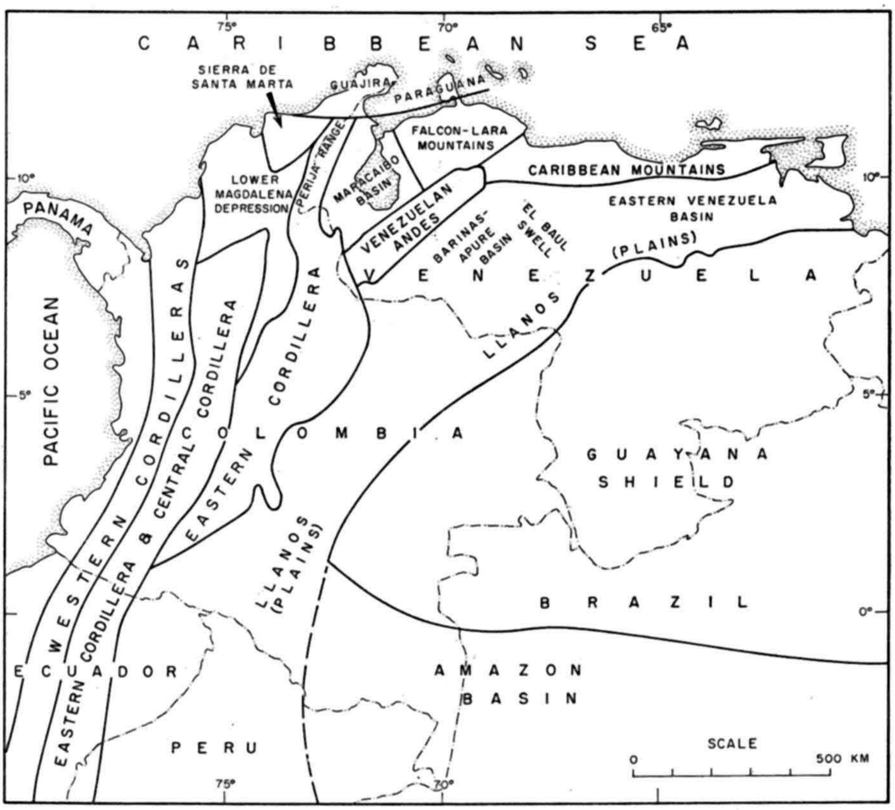


Fig. I – 1. Morphological and structural provinces of northwestern South America. After LIDDLE (1928), STAFF etc. (1948), BUCHER (1952), YOUNG *et al.* (1956), and H. J. HARRINGTON (in JENKS, 1956).

Along the Pacific border of the South American continent the high mountain ranges of the Andes are found. They can be divided into two mountain ranges in Ecuador, and into three mountain ranges in Colombia. The Western Cordillera of Ecuador continues as the Western Cordillera of Colombia, until it terminates at the Caribbean coast (one branch joins the Darien Mountains of Panama). The Eastern Cordillera of Eduador continues northwards as the Central Cordillera of Colombia, until it terminates at the Lower Magdalena Depression. In Colombia there is a third range, the Eastern Cordillera, which originates in southern Colombia and farther north becomes separated from the Central Cordillera by the valley of the Magdalena River. The most northern part of the Eastern Cordillera forms the political boundary between Colombia and Venezuela under the name of Perija Range (Sierra de Perijá).

To the north of the Lower Magdalena Depression the Sierra de Santa Marta is situated. This massif is in a somewhat special position due to its geographical isolation. It may be the northern continuation of the Eastern Cordillera or of the Central Cordillera, but other interpretations are possible as the structural grain of the massif is essentially east-west (A. A. OLSSON, in JENKS, 1956).

In Colombia the age of these Andean mountain ranges is Tertiary, but movements possibly lasted into the Quaternary. The Central Cordillera was a source of sediments already in late Cretaceous times. The Western and Central Cordilleras are of predominantly igneous and metamorphic composition, the Eastern Cordillera is largely made up of sediments.

East of the Andes Ranges lie the Llanos (plains), the Amazon Basin, and the Guayana Shield.

The Llanos are vast plains of almost flat-lying Tertiary and Quaternary beds overlapping to the east the basement rocks of the Shield. In the subsurface, marine Cretaceous and Tertiary thin and become continental towards the Guayana Shield. The Guayana Shield is composed of Pre-Cambrian basement rocks with a covering of continental sediments (Roraima formation) of uncertain though probably Mesozoic age in the central part. The Amazon Basin is composed of marine and continental sediments of Palaeozoic to Quaternary age.

The morphological and structural provinces which are partly or entirely situated inside Venezuelan territory were for the greater part introduced by LIDDLE (1928). Most of the information below is due to him, but additional information has been incorporated from other works, referred to below.

The Guayana Shield in Venezuela is an elevated plateau averaging from 350 to 500 metres above sea level. On this plateau there are a great number of low hills which increase in height towards the south and south-east. Near the border with Brazil this type of topography is replaced by high mountain ranges; Mount Roraima on the Guayana boundary is 2730 metres above sea level. The Shield is composed of Pre-Cambrian basement rocks (gneisses, granites) with, in the central part, a covering of continental sediments. The approximate northern limit of the Guayana Shield is formed by the Orinoco River.

The Venezuelan Llanos are situated between the Orinoco to the south and the Caribbean Mountains and the Venezuelan Andes to the north and northwest. The Llanos comprise the most uniform physiographic unit in Venezuela; throughout their whole extent they are slightly rolling or undulating plains with occasionally slightly higher areas. Elevations of more than 200 m above sea level only occur in the eastern part; elsewhere the elevations are always less.

Geologically, the Venezuelan Llanos can be divided into two distinct basins: the Barinas-Apure Basin and the Eastern Venezuela Basin. The Barinas-Apure Basin contains a thick series of mainly marine sediments ranging in age from Cretaceous to Eocene, covered by a thick layer of predominantly fluviatile deposits (largely of Andean origin) laid down in Oligocene, Miocene, and possibly Pliocene times. These are in turn covered by terrestrial Quaternary sediments.

The structure of the Barinas-Apure Basin has not been discussed in detail in the published literature. A generalized section, presumably largely based on geophysical evidence, has been published by YOUNG *et al.* (1956, Fig. 14). The Andes margin shows overthrusts towards the southeast. The Pre-Cretaceous basement is at about 4 km below sea level in its deepest part. The basin quickly shallows towards the southeast.

The Eastern Venezuela Basin contains sediments of Cretaceous to Quaternary age. The thickness of the sediments in the deepest part of the basin is probably more than 40,000 ft (more than 12 km) (HEDBERG, 1950, 1956).

The two basins are separated by the El Baul Swell, a gently sloping barrier which received its name from the town of El Baul near which Pre-Cambrian igneous and metamorphic rocks as well as Cambrian sediments emerge from beneath the alluvial deposits of the Llanos.

In Venezuela, the northwestern and northern border of the Llanos is formed by the Venezuelan Andes and the Caribbean Mountains respectively. The Caribbean Mountains (which, following BUCHER (1952), comprise the Cordillera de la Costa or Coast Range, and the Serranía del Interior or Inner Range) reach their greatest elevation in the Caracas region (about 2800 m). Their western part is largely made up of metamorphic rocks, the greater part of which are now, after having been considered for a long time as much older, thought to be of Cretaceous age. Both acid and basic igneous intrusives are common. The most important orogeny, which produced the major folding and the chief intrusions and metamorphism in the western part of the Caribbean Mountains, took place in late Cretaceous time.

The eastern part of the Caribbean Mountains is in many respects similar to the western part; here too there is a belt of more or less metamorphic rocks in the north and non-metamorphic Cretaceous and Tertiary sediments in the south.

The Venezuelan Andes is the name given to a straight mountain range running southwest-northeast in the western part of Venezuela. It is flanked in the northwest by the Maracaibo Basin and in the southeast by the Barinas-Apure Basin. Topographically, it is best defined as being situated between the 100 m contour on the northwestern side and the 200 m contour on the southeastern side. Between these limits, it is 100 km wide. Its central part comprises two parallel, southwest-northeast trending ranges, separated by the valleys of the Rio Chama and the Rio Motatan. The northwestern range is called Cordillera del Norte, and comprises peaks of up to 4620 m elevation. The southeastern range is called Cordillera de Mérida, the highest peak of which is the highest peak in Venezuela (Pico Bolívar, 5007 m).

The Venezuelan Andes are separated from the Eastern Cordillera in Colombia by the Tachira Depression (also called Tachira Watershed or Tachira Gap), a roughly saddle-shaped area of low elevation.

To the northeast the Venezuelan Andes also diminish in elevation. The boundary between the Venezuelan Andes and the Caribbean Mountains is usually drawn through Barquisimeto (elevation 564 m). The length of the Venezuelan Andes between these limits is about 400 km.

The Tachira Depression and the Barquisimeto area are essentially composed of folded and faulted Cretaceous and Tertiary sediments. The Venezuelan Andes are mainly formed by Pre-Cretaceous rocks which appear from underneath this younger cover. Tertiary and Cretaceous sedimentary rocks are exposed along the flanks of the range.

The Pre-Cretaceous rocks which form the Venezuelan Andes are igneous and highly metamorphic rocks of Palaeozoic and Pre-Cambrian age, more or less metamorphic sediments of Palaeozoic age, and the prevalently red and green clastic sediments of the La Quinta formation of probably Triassic-Jurassic age.

Orogenic movements started in late Eocene – early Oligocene times and apparently reached their maximum in Mio-Pliocene times. In Pliocene time the Venezuelan Andes acquired the shape and probably most of the elevation they have today.

Only the major features of the structure of the Venezuelan Andes are known. L. KEHRER (in JENKS, 1956, p. 342) has described it as follows:

"The structural plan of the Andes is quite different from that of the Alps in that there are no large overthrust sheets of Decken and Klippen. The pattern is more similar to that of the Canadian Rocky Mountains; it is in principle a high and complex fan-fold with upthrusts or reverse faults at the outer flanks (involving beds from the Precambrian to Eocene) and tension faults in the more central parts. Foredeeps, clearly evidenced also by geophysical results, follow both flanks and are deeply filled with Nagelfluh conglomerates and Molasse sandstones, which represent the Tertiary denudation products from the already elevated post-Eocene Andes".

Geological sections of the Venezuelan Andes have been published by KÜNDIG (1938), MILLER *et al.* (1955, sections by K. HABICHT), and by DUFOUR (1955, section by L. KEHRER and O. RENZ).

The Falcon-Lara Mountains constitute an area where elevations do not exceed 2000 m. Low mountain ranges are encountered which are arcuately arranged with respect to the Venezuelan Andes and the Caribbean Mountains. Sedimentary thicknesses are great, the Post-Eocene beds alone reach a thickness of several thousands of metres.

The Maracaibo Basin occupies a low topographical and structural depression between the Perija Range to the west, the Venezuelan Andes to the southeast, the Falcon-Lara Mountains to the northeast, and the Guajira-Paraguana province to the north. In a north-south direction it measures about 330 km, in an east-west direction about 240 km. The centre of the basin is cocupied by the Lake of Maracaibo (also called Lake Maracaibo) which has an area of about 12,000 square kilometres.

Geologically speaking, the formation of the Maracaibo Basin, as we know it today, was quite recent. During Mesozoic times geological history was nearly identical over all of western Venezuela. During Eocene times marked differences in facies developed in different areas, but it is not till the Oligo-Miocene that one can distinguish the Maracaibo Basin as such. The total thickness of Cretaceous to Recent sediments in the Maracaibo Basin in some areas is known to exceed 10 km.

The Post-Eocene sediments (comprising all sediments deposited after the Eocene) thin rapidly away from the Andes. Along the northwestern front of the Venezuelan Andes the thickness of Post-Eocene sediments alone is about 7.5 km (25,000 ft), in the centre of Lake Maracaibo it is 3 – 4.5 km (10,000 to 15,000 ft), in the northern part of the Maracaibo Basin it is about 1.5 km (5,000 ft).

The structure of the Maracaibo Basin is in essence very simple. Pre-Cretaceous rocks crop out along its margins except in the northeast. From the Perijá Range the Pre-Cretaceous basement dips down towards the Venezuelan Andes. It reaches its greatest depth (more than 10 km) in the trough along the northwestern border of the Venezuelan Andes. Folds and faults are common, but compared with the general size and shape of the basin they are of secondary importance. Geological sections, partly based on geophysical results, can be found in publications by MILLER *et al.* (1955) and DUFOUR (1955).

The Guajira-Paraguana province comprises the Guajira and Paraguana peninsulas, both low-lying areas with some hills of little elevation (not exceeding 900 m) and both arid regions. The province also includes the northern part of the Gulf of Venezuela between these peninsulas, as well as the islands of Aruba, Curaçao, and Bonaire.

b. *Contrary movements of the Venezuelan Andes and adjacent basins*

One striking deduction to be made from the geological history and structure of the western part of Venezuela is that as the Andes rose progressively in Post-Eocene times, the adjacent areas developed into deep basins. Today, the highest part of the Venezuelan Andes (Pico

Bolívar), which is carved out of Pre-Cretaceous rocks, is just over 5 km above sea level whereas the Pre-Cretaceous basement lies at more than 10 km depth below sea level in the deepest part of the Maracaibo Basin and at about 4 km below sea level in the deepest part of the Barinas-Apure Basin. The close relation between the rise of the Andes and the subsidence of the immediately adjoining parts of the adjacent basins (the Maracaibo Basin in particular) has been stressed by SUTTON (1946), STAFF etc. (1948), BUCHER (1952), and MILLER *et al.* (1955). In this investigation it will be endeavoured to account for these observations when discussing the interpretation of the gravity results.

At present, many authors believe that there is evidence for continuing uplift of the Andes. The widespread occurrence in parts of the Venezuelan Andes of terraces formed by presumably Pleistocene valley floors (KÜNDIG, 1938, p. 40; OPPENHEIM, 1938, p. 28), the tectonic deformation of such terraces (BUCHER, 1952, pp. 17–18, L. KEHRER in JENKS, 1956, pp. 342 and 349), the very young topography (BUCHER, 1952, p. 17) and the high seismicity of the Venezuelan Andes (BUCHER 1952, p. 17) may indicate that movements continued into the Pleistocene and may still continue.

The occurrence of terraces is usually considered to constitute the best evidence for recent uplift. However, as Ph. H. KUENEN of Groningen University pointed out (personal communication), uplift of the Venezuelan Andes does not give a satisfactory explanation for the terraces of this region (locally called mesas, from Spanish mesa = table). The terraces are developed on the surface of an extremely thick and coarse valley fill into which the rivers have recently cut deep gorges. Some are V-shaped, apparently without reaching the ancient valley floor. Others are wider but nowhere cut very far into the rocky substratum. The terrace surfaces slope gradually upwards to levels of 2000 m at least. Changes of sea level cannot be invoked as the cause because the distance from the coast and the thickness of the fill are too large. The most probable explanation is a climatic change. First the balance was upset and the valleys were choked with debris. With the return to former conditions a clearing out started which has not yet succeeded in removing all the fill.

In Lake Maracaibo and in the swamps and lowlands at its southeastern end, sedimentation and possibly subsidence also, still continue today.

II. SUMMARY OF GRAVIMETRIC WORK IN VENEZUELA

Venezuela has been covered by an extensive network of gravity observations. The gravity data made by or on behalf of the Cía. Shell de Venezuela consist of torsion balance sections dating from the earliest period, as well as Holweck-Lejay pendulum stations, Thyssen and more modern gravimeter surveys.

The network of Holweck-Lejay pendulum stations is based on De Bilt (Netherlands) and Curaçao (Netherlands West Indies). The general level of this gravity network is considered by DE BRUYN (1951) to be correct within a few milligal. This view can now be confirmed by some new data.

The Shell gravity network in Venezuela is based on a gravity station in the old Caribbean Petroleum Company office in Caracas. Its geographical latitude is 10° 31′ North, its height 935 m, and the accepted value of gravity is $g = 978.068$ cm/sec^2. In Caracas there are also three gravity stations which are connected to the world-wide gravity network (WOOLLARD, 1950, 1956) established by Professor G. P. WOOLLARD of the University of Wisconsin, U.S.A., and his associates. The relevant data for these stations are shown in Table II – 1. The world-wide gravity network is based on the Commerce Building gravity base at Washington, D.C., for which a value of $g = 980.1190$ cm/sec^2 has been accepted (WOOLLARD, 1950). The average modified value (i.e., the observed value reduced to the same height and latitude as the Shell station with which the comparison is made) for the Woollard stations in Caracas is about 7 mgal lower than the Shell value.

TABLE II – 1

GRAVITY STATIONS IN CARACAS, VENEZUELA

Station	Lat.	Height	g (cm/sec^2)	Modified value**
C.P.C. Office, Caracas	10°31′	935 m	978.068	978.068
Caracas Observatory*.	10°30′30″	1040 m	978.0378	978.059
Cartographia Nacional, Caracas*.	10°30′40″	925 m	978.0665	978.065
Loma Quintana, Caracas* . . .	10°30′20″	1078 m	978.0290	978.058

* Stations connected to Woollard's world-wide gravity survey. Gravity values kindly supplied by Professor G. P. WOOLLARD.

** Modified value is observed value reduced to same height and latitude as Shell station.

This kind of comparison assumes that the terrain corrections as well as the Bouguer anomalies are the same for all stations. This is unlikely to be so; hence it may be better to compare the two stations of most nearly the same height thus reducing the change in terrain effect. The station which fulfils this condition is the Cartographia Nacional station. Its modified value is only 3 mgal below the Shell value.

In Maracaibo a second comparison with the world-wide gravity network can be made. The result is shown in Table II – 2.

TABLE II – 2

COMPARISON OF GRAVITY VALUES IN MARACAIBO, VENEZUELA

Station	Lat.	Height	Bouguer anomaly (mgal)	g (cm/sec²)
Airport*	10°40′20″	55 m	—	978.1986
Airport**	10°40′20″	55 m	—14.5	978.199

* Station connected to Woollard's world-wide gravity survey. Gravity value kindly supplied by Professor G. P. Woollard.

** Interpolated between Shell gravity stations.

In Maracaibo the two values agree exactly. For these stations the difference in terrain effect and Bouguer anomaly is quite negligible, and this is consequently the most reliable comparison. The general level of the Shell gravity network is therefore probably essentially correct.

All gravity observations outside the Venezuelan Andes have been reduced by using the 1930 International Formula for normal values of gravity, more fully referred to later. The density used for the topography above sea level is 2.1 g/cm³. This figure is believed to be correct as stations outside the Venezuelan Andes are all situated on lowlying Quarternary deposits.

Stations near the Venezuelan Andes require a terrain correction (also referred to as topographical correction). This correction will be discussed below. Elsewhere the terrain corrections are negligible.

One group of older gravity observations requires a separate discussion. A number of Holweck-Lejay pendulum stations are available in the Tachira area, near the southwestern extremity of the Venezuelan Andes. These observations were made about 20 years ago and their observed gravity values are considered to be accurate only to within about 5 mgal. They are shown in fig. II – 1 with their appropriate data.

The reductions were made using density 2.67 for all stations and following the same procedure as that used for the gravimeter stations in the central Venezuelan Andes, to be described below. The terrain correction (or topographical correction) shown in Fig. II – 1 is the correction for topography above or below station height for Hayford's zones A–O_2 and density 2.67. For the computation of the terrain

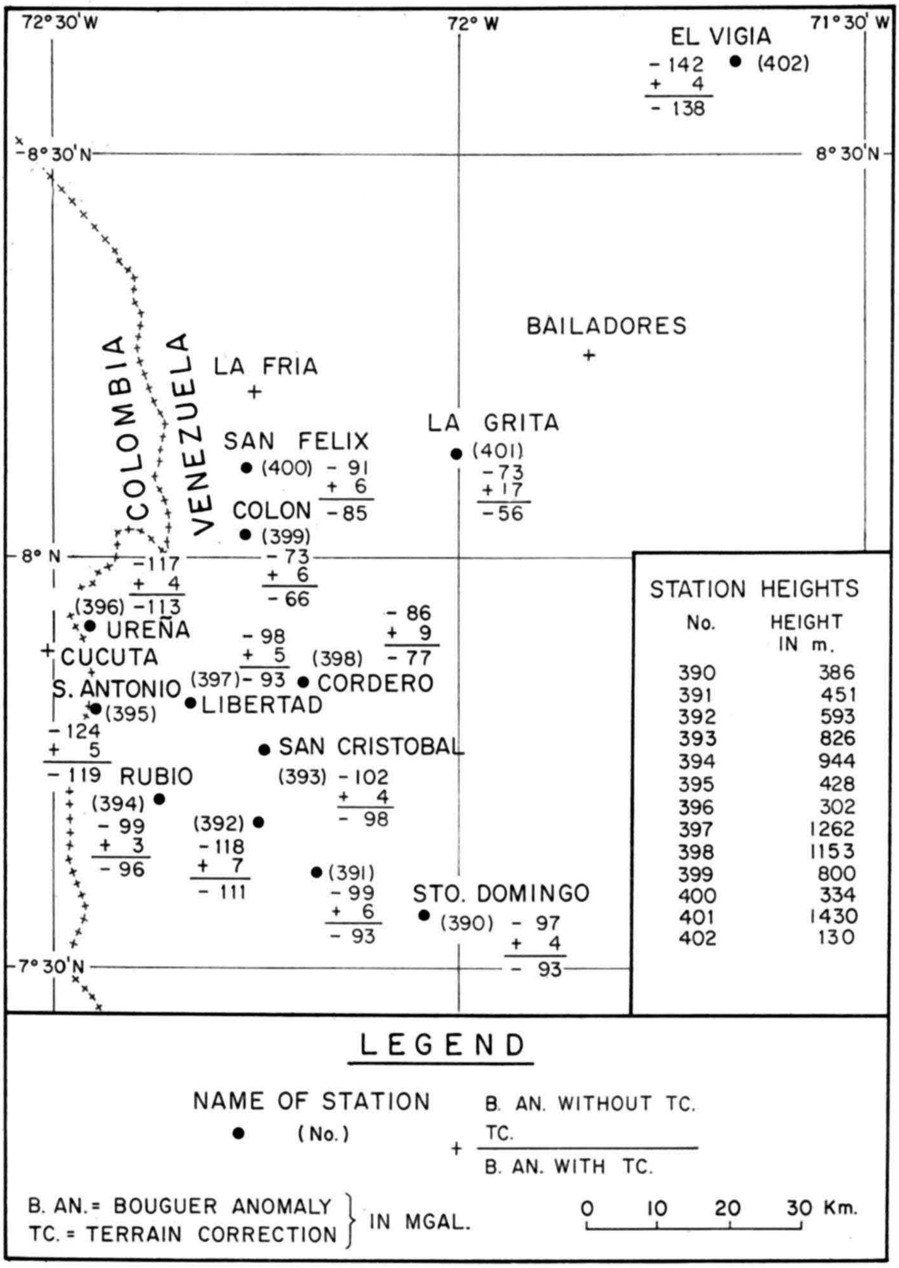


Fig. II – 1. Holweck-Lejay pendulum stations in the southwestern part of the Venezuelan Andes (Tachira area).

corrections contour maps on scales 1:100,000, 1:500,000 and 1:1,500,000 were available. These maps are listed in the section dealing with terrain corrections in the central Venezuelan Andes.

Due to small uncertainties in the position of these old Holweck-Lejay pendulum stations the terrain corrections are only correct within 10 %. This inaccuracy is negligible in comparison with the inaccuracies in the observed gravity values.

These older stations are of interest only because they supply the only gravity information available in this part of Venezuela.

The above-mentioned gravity data (to be shown on a later compilation map) do not cover the Venezuelan Andes. In order to obtain reliable information, a special survey has been carried out along main highways in the central Venezuelan Andes. This survey will now be described.

III. GRAVITY SURVEY OF THE CENTRAL VENEZUELAN ANDES

a. *General remarks*

The Shell gravity party which carried out this gravity survey consisted of:

R. B. COMER, Party Chief
P. G. SLUITER, Surveyor
One gravity observer
One driver
One surveyor's assistant

One of the authors (J.H.) took part in the survey in an advisory capacity.

The party had three vehicles at its disposal, namely one Landrover and two Power Wagons.

MR. COMER, assisted by the gravity observer, carried out the greater part of the gravity measurements and the barometric observations. MR. SLUITER, helped by his assistant, was in charge of the surveying of the immediate surroundings of the gravity stations, as well as of locating stations on the 1:100,000 maps. The participating author supervised the first series of gravity observations and made the first series of barometric observations. He also selected the station sites and collected rock samples for density determinations.

The survey was carried out between 4th and 21st May 1956. The party was based on Barinas, Timotes, and Merida successively. In the higher parts of the Andes work was often hampered by low temperatures, rain, fog, and occasionally sleet. The survey was made along the following roads (Fig. III – 1).

1) The road from Barinitas, via the Paramo de Mucuchies (4040 m above sea level), and Timotes, to Valera.
2) The road from the Paramo de Mucuchies, via Merida, and Egido, to Lagunillas.
3) The road from Egido, via La Azulita, to the Panamerican Highway (Carretera Panamericana).

A total of 49 stations were established.

b. *Position and latitude of gravity stations*

Stations were established on flat areas in order to minimize terrain corrections for the immediate surroundings of the stations. However, it was not always possible to avoid unfavourably situated stations for the simple reason that flat areas did not occur. In the Sto. Domingo valley,

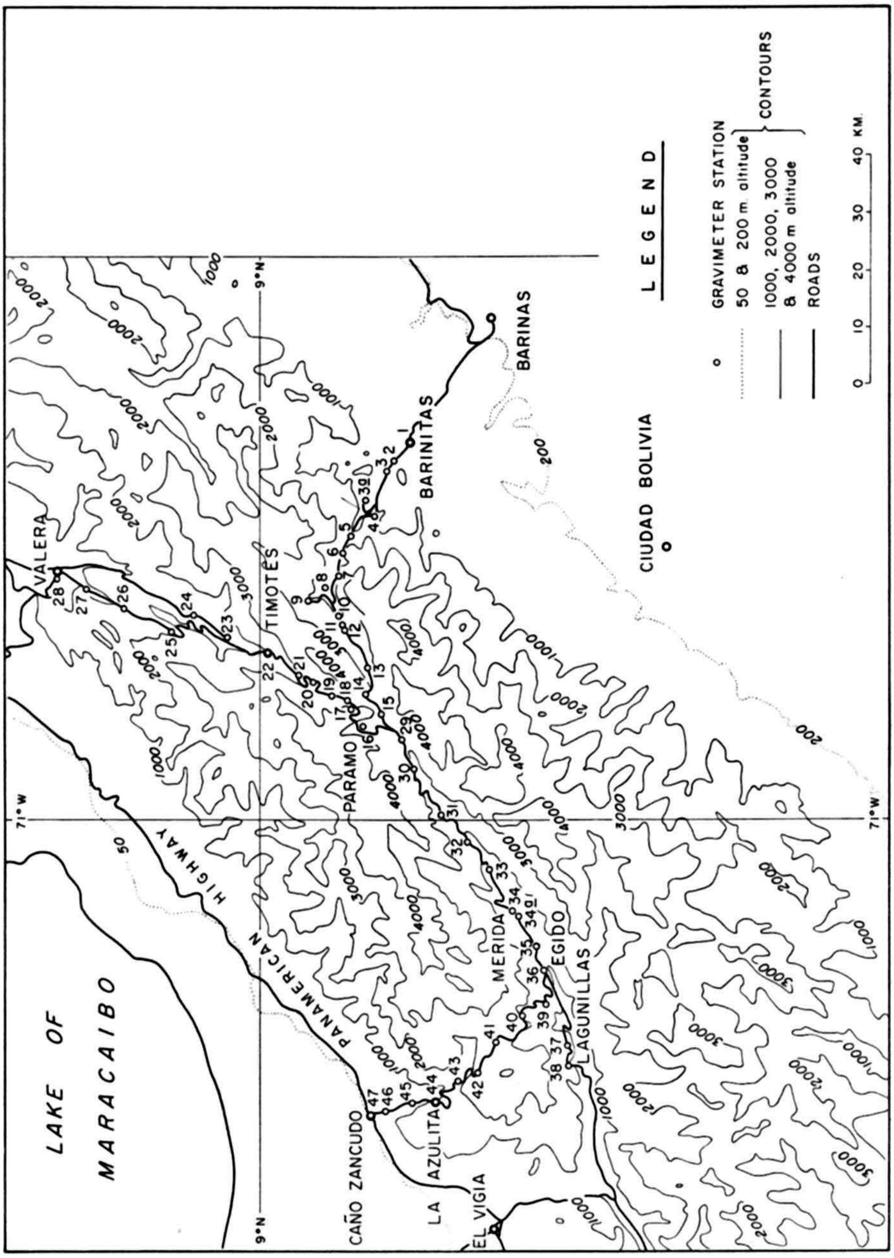


Fig. III – 1. Gravimeter stations in the central Venezuelan Andes.

for example, the only reasonably flat area between our stations Cochinilla and Pueblo Llano, about 40 km apart, is at Altamira. Other stations therefore, had to be established along the road passing through the steepest part of the valley.

The same difficulty was encountered for stations between Sto. Domingo and the Paramo de Mucuchies, as well as between the latter and Chachopo.

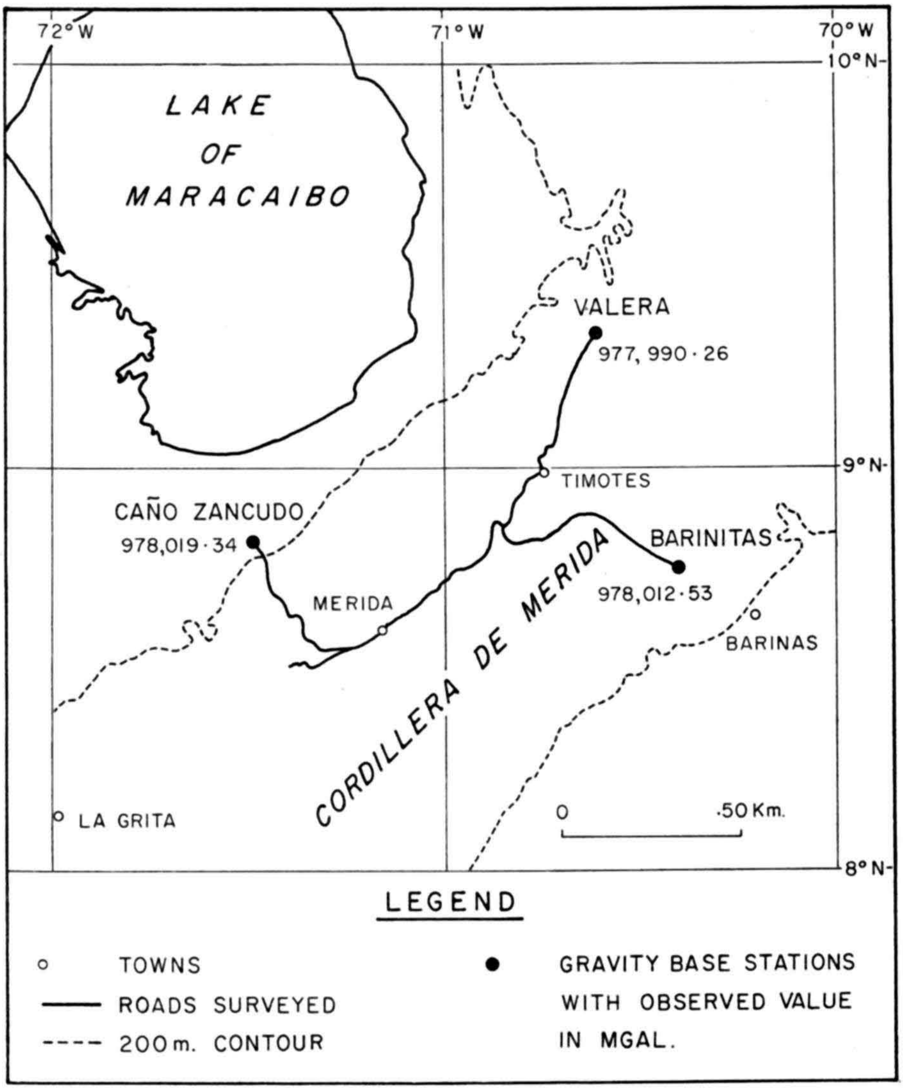


Fig. III – 2. Gravity stations used as base stations for Andes survey.

These facts have a direct bearing on the accuracy of the terrain corrections; this will be discussed below.

The geographical coordinates of the station sites were read from 1:100,000 topographical maps prepared by the Cía. Shell de Venezuela, after the exact position of the station on the map had been determined, if necessary by surveying. The latitude of the station, thus obtained, is probably correct within 30″. This corresponds to an uncertainty of about 0.25 mgal in the latitude correction.

The immediate surroundings of the station were surveyed with a view to preparing a contour map of the country extending to 1000–2000 m around each station. Elevations were determined relative to the station elevation.

c. *Gravity measurements*

For the gravity survey of the Andes, three stations, occupied during earlier conventional surveys, were used as base stations. They are situated in Barinitas, Valera, and Caño Zancudo (Fig. III - 2). The observed values of gravity at these points, as established during the earlier surveys, have been accepted without change.

The highest new gravity station occupied is that situated on the Paramo de Mucuchies, at 4044 m above sea level. This station is connected to Barinitas, Valera, and Caño Zancudo by means of respectively 8, 8, and 16 intervening main stations. Other stations (situated either between main stations or off the main roads) were connected to one or more of these main stations.

The instrument used was a La Coste-Romberg Gravity Meter (No. 72). This instrument can be read to within 0.01 mgal; its range is about 150 mgal. As the observed gravity value changes by more than 700 mgal between any of the base stations and the Paramo de Mucuchies, the range of the meter had to be frequently reset. The drift of the instrument is about 0.1 mgal per hour. Its calibration factor is kept under observation by measurements between gravity stations established for the purpose by the Cía. Shell de Venezuela.

The gravity meter was transported by car, using the car battery to supply the current needed for the heater element and light bulbs.

To find the gravity difference between two stations a and b, readings were taken in the chronological order a b a b; the time was also read. This yields two values for the gravity difference, corrected for the combined influence of tidal effects and instrument drift. Their average was used for further computations. The elapsed time between repeat measurements was never more than 75 minutes, usually it was less than 1 hour.

In the table below (Table III - 1) the measured gravity differences between the base stations are compared with the known differences (cf. Fig. III - 2).

TABLE III - 1

GRAVITY DIFFERENCES BETWEEN BASE STATIONS

Base station	Observed gravity value (mgal)	Known difference (mgal)	Measured difference (mgal)	Correction (mgal)
Valera	977,990.26	—22.27	—20.47	—1.80
Barinitas	978,012.53			
Caño Zancudo . . .	978,019.34	+ 6.81	+ 9.12	—2.31

N.B. Differences are taken relative to Barinitas.

It will be seen from this table that the known and the measured differences between Valera and Caño Zancudo differ by only 0.51 mgal, whereas there is a much larger discrepancy between Barinitas (southeast of the Andes) on the one hand, and Valera and Caño Zancudo (both northwest of the Andes) on the other. This may indicate that there is an error of 1–2 mgal in the tie between the plains on both sides of the Venezuelan Andes, the earlier connection between the Lake Maracaibo area and the Llanos having been made through Barquisimeto, to the northeast of the Venezuelan Andes. For our purpose, however, such a discrepancy is insignificant. The gravity measurements in the Andes have therefore been adjusted by distributing the correction equally among the main gravity stations.

The gravity values at main stations are estimated to be accurate within 0.1 mgal; those at secondary stations are also correct within the same limits.

The position of the gravity stations is shown in Fig. III – 1.

d. *Determination of station heights*

Of the 49 gravity stations occupied in the Andes, 9 were situated at or in the immediate neighbourhood of government bench marks. A further 2 stations were situated on earlier gravity stations of which the height was thus known. The remaining 38 station heights were determined by barometer. In addition to the known heights just mentioned, another bench mark was used at Apartaderos for the purpose of barometric levelling only (Fig. III – 3).

Series of main stations were established between points of known altitude. Stations in between main stations or stations off the main road were subsequently connected to the main stations.

The barometers used were two Surveying Micro Altimeters, manufactured by American Paulin System, Los Angeles, U.S.A. These barometers have a scale calibrated in meters, which can be read to within 0.2 m. The instruments are so constructed that the temperature has no effect on the instruments themselves, though, of course, a correction must always be made for the actual air temperature when surveying. The barometers are calibrated for a temperature of 50° F, that is, the barometer records true differences in elevation when the air temperature is 50° F. Assuming no change in atmospheric pressure, the true elevation difference of two stations can be found by adding to or subtracting from the difference read a correction of 0.1 % for each degree by which the sum of the air temperatures at the two stations exceeds (respectively is exceeded by) 100 ° F.

Changes in atmospheric pressure in the course of the day were corrected for by repeat measurements. To this end the two barometers were transported by the same vehicle that carried the gravimeter. The difference in elevation between two stations a and b was determined by reading both barometers, the thermometer, and the time at these stations in the chronological order a b a b. This yields for each barometer two values of the elevation difference corrected for daily variation and differences in air temperature. For further computations the average of the four values was used.

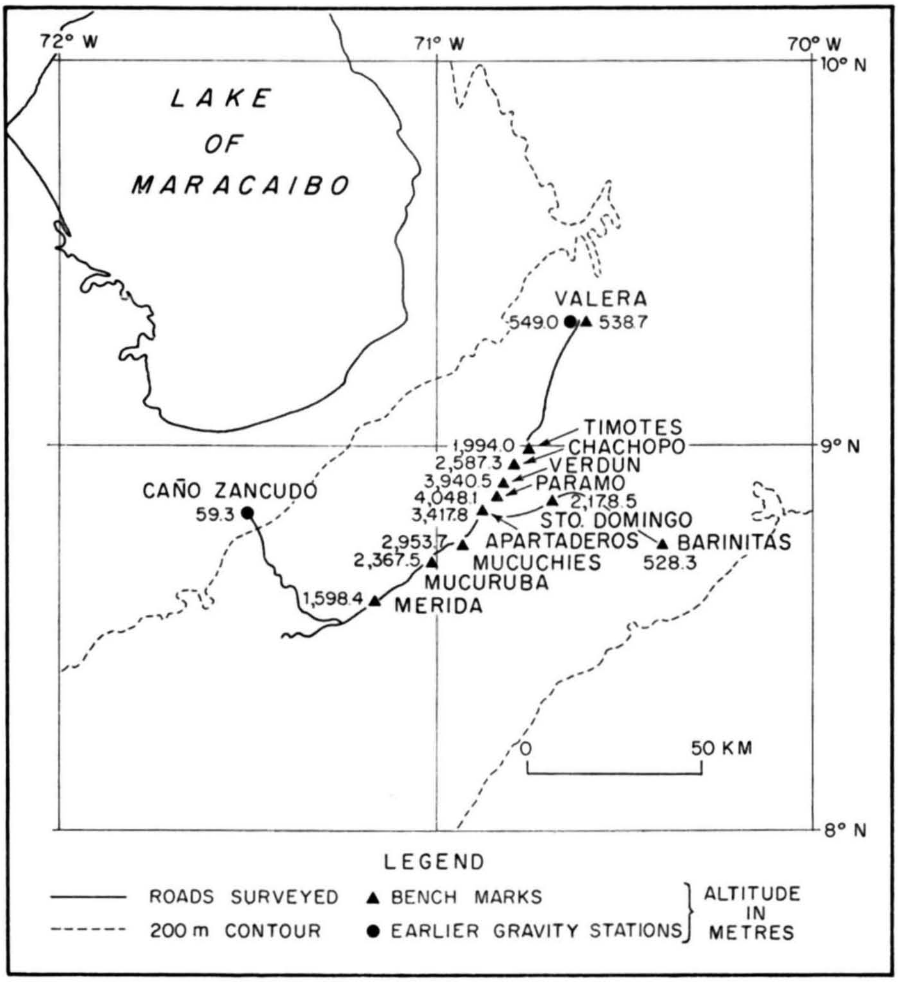


Fig. III – 3. Points of known altitude used for barometric levelling.

The elapsed time between repeat measurements at the same station was never in excess of 75 minutes, usually it was less than 1 hr. This short time between repeat measurements, as well as the fact that there are four independent measured elevation differences available for each pair of successive stations, guarantees a satisfactory elimination of changes in atmospheric pressure due to other causes than differences in elevation.

For the purpose of illustration a series of observations of the daily variation of atmospheric pressure at Barinas is shown (Fig. III – 4). The change is expressed in metres apparent altitude; as the pressure decreases, the apparent altitude increases, and vice versa. It is obvious that in the mountains, where atmospheric conditions are often less stable than in the plains, the daily variation is more erratic. However, the procedure of repeat measurements should successfully eliminate any possible errors due to this cause.

The elevation scale of the barometers is calibrated not only for a certain air temperature (50° F), but also for a certain geographical latitude, a certain moisture content of the air, and a certain elevation. The sum of the measured elevation differences between main stations connecting points of known height, therefore,

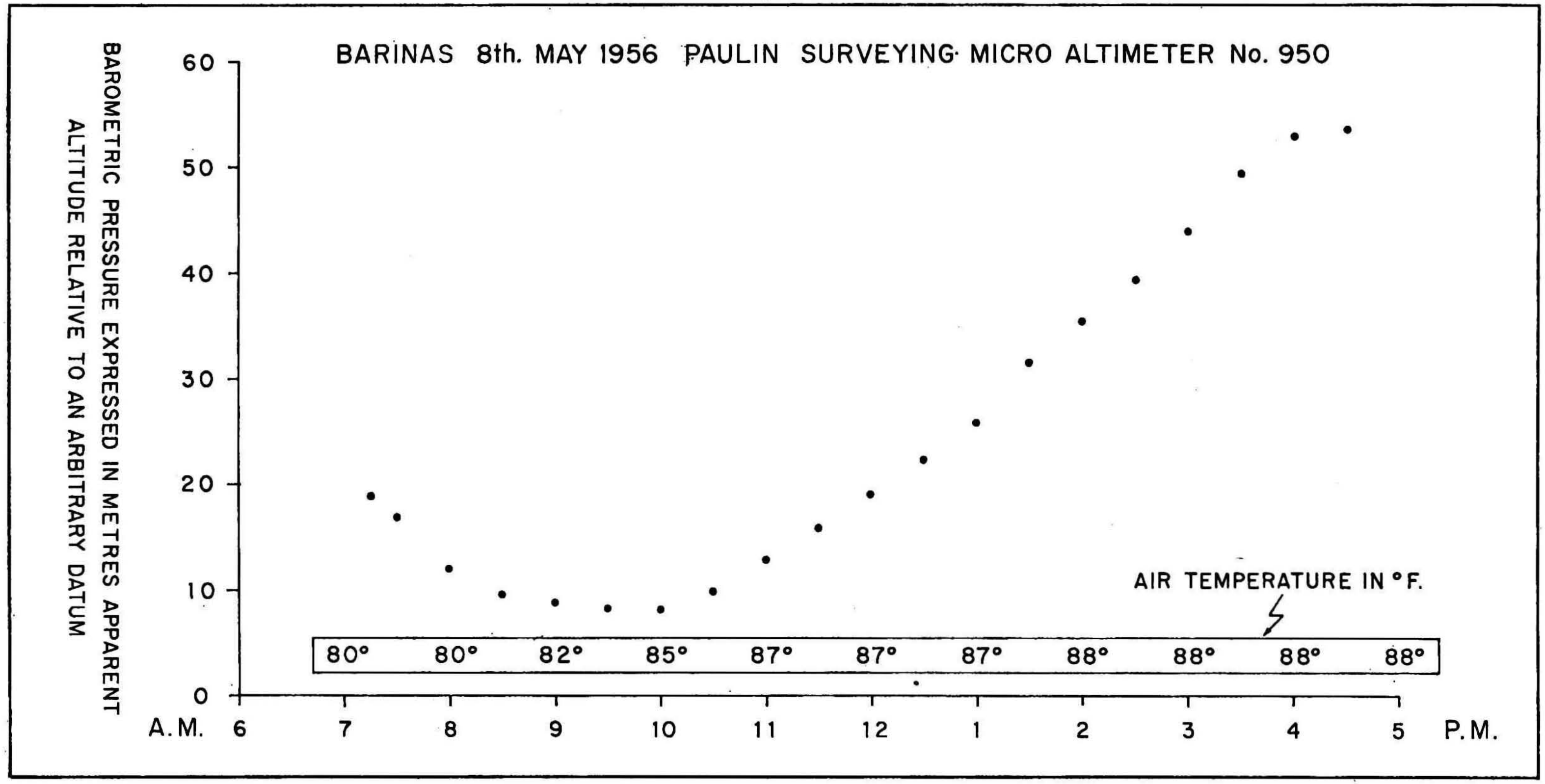


Fig. III – 4. **Observations of the daily variation of the atmospheric pressure. The increase in apparent altitude during the day corresponds to a decrease in atmospheric pressure.**

does not exactly agree with the known true elevation differences. The correction to be applied to the measured differences was always found to be negative; on the average it was —0.8 %. The correction was equally distributed between all intervening main stations.

For stations between Merida and Caño Zancudo (on the Panamerican Highway) there was no other altitude control for barometric levelling than that of the ends (Fig. III - 3). Station heights here are therefore somewhat less accurate than elsewhere. For stations between Merida and Caño Zancudo the elevations are estimated to be correct within less than 7 metres, corresponding to an uncertainty of about $1\frac{1}{2}$ mgal or less in the Bouguer anomaly. Elsewhere the uncertainty is estimated at less than 5 metres, corresponding to an uncertainty of 1 mgal or less in the Bouguer anomaly. Stations between main stations, or stations off the main road, were connected to the main stations by the same procedure as described above. The uncertainty in their elevations is practically the same as that of the main stations to which they are connected.

e. *Density of the central Venezuelan Andes*

A detailed analysis of rock densities in the central Venezuelan Andes has been made. This analysis is based on 96 samples, collected from exposures along the same roads as those along which the gravity survey was made. The results have been discussed elsewhere (HOSPERS and VAN WIJNEN, 1958).

The average bulk density found for the central Venezuelan Andes is 2.670 g/cm³. This figure can be confidently used for all corrections into which the density of the topography of the Andes enters.

IV. REDUCTION OF GRAVITY OBSERVATIONS IN THE CENTRAL VENEZUELAN ANDES

a. *Normal values of gravity*

For the normal values of gravity the 1930 International Formula

$$g = 978.0490\ (1 + 0.0052884\ \text{sine}^2 L - 0.0000059\ \text{sine}^2 2L)\ \text{cm. sec}^{-2}$$

where g is the normal value and L the latitude, has been used. The values according to this formula have been tabulated by W. D. LAMBERT and F. W. DARLING. These tables have been reproduced by NETTLETON (1940; pp. 137–143).

b. *Free-air corrections*

For the free-air correction we have used the formula (LEJAY, 1947:)

$$\text{free-air correction} = +0.30857\ h\ \text{mgal},$$

where h is the height of the station (in metres). A more accurate factor can be computed which makes it possible to allow for the change in the vertical gradient of gravity with geographical latitude. This more accurate factor, however, does not significantly improve the accuracy; it has therefore not been used.

The vertical gradient of gravity also depends on the altitude. However, the possible improvement in accuracy is small and hence the effect has been neglected in order not to complicate the computations further.

c. *Bouguer corrections*

For the correction of the effect of all topography up to the outside of Hayford's zone O_2 (at 166.735 km from the station) extensive use has been made of P. Lejay's book: "Développements modernes de la gravimétrie" (LEJAY, 1947).

Instead of subtracting from the measured gravity value the effect of a horizontal slab of infinite extent and density 2.67 (Bouguer correction) one subtracts the effect of a cap or spherical plateau (Lejay's "calotte sphérique") extending to the outside of zone O_2, having the station altitude for its height, and density 2.67.

The correction for the gravitational effect of the cap or spherical plateau extending to the outside of zone O_2 may be combined with the free-air correction. This has been done by LEJAY; his table III makes it possible to determine at a glance the combined effect of spherical plateau and free-air correction (LEJAY 1947, Table III, pp. 230–231). The value of this correction has been shown in the table of gravity stations (Table IV – 1) under the heading "Lejay correction".

d. *Topographical corrections*

Finally, corrections must be made for the fact that the actual topography up to the outside of zone O_2 deviates from the surface of the spherical plateau of station height. The authors have followed LEJAY in this, accepting his division of the topography into the Hayford zones A–O_2 and of the individual zones into compartments, and using his Table IV LIEJAY, 1947, pp. 232–235) to find the appropriate corrections which are .gven as a function of the deviation of compartment heights from the (station height. The density for which the tables are computed is 2.67

For the determination of compartment heights the following maps were used:

a) Topographical maps on scale 1:5,000 of each station site, surveyed on the spot by Mr. P. G. SLUITER.

b) A topographical map on scale 1:100,000 with contours at 100 m intervals of the Rio Chama valley from Mucuruba to Egido, prepared by the Caracas Topographical Department of the Cía. Shell de Venezuela.

c) A topographical map on scale 1:500,000 with contours at 200 m intervals of the entire Venezuelan Andes (same author as map b.).

d) A topographical map of Venezuela on scale 1:1,500,000 with contours at 100, 200, 1000, 2000, 3000 and 4000 m (Shell map of Venezuela).

Compartment heights for zones B–F_1 (incl.) were taken from the maps under a, for zones F_2–L (incl.) from map c, for zones M–O_2 (incl.) from map d. Where possible, map b. was used for zones F_2–I instead of map c. Difficulties were encountered when station site maps (maps a) did not extend far enough to get all or any compartments in zone F_1 or nearer zones, or when abrupt relief changes made readings of zones F_2 and farther difficult on map c. Occasionally, therefore, recourse had to be taken to height estimates based on interpolations between known zones or, sometimes, on aerial photographs. However, it is thought that the computed topographical corrections are still sufficiently accurate for the present purpose. It is estimated that the computed topographical corrections listed in Table IV – 1 are accurate within about 5 %, except for stations 5, 6 and 7 (cf. Table IV – 1).

It will be noted that one cause of possible systematic errors has been avoided by referring all measurements at the station site to station height. In this way, the topographical correction for the inner zones is not affected by uncertainties in the station height. For the other zones the effect is negligible.

e. *Bouguer anomalies*

By subtracting the normal value of gravity from the observed value, adding the free-air correction, subtracting the spherical plateau correction (the latter two are combined in one operation), and finally adding the topographical correction, an anomaly is obtained which will be referred to as the Bouguer anomaly. (The original Bouguer anomaly did not include the topographical correction, and used a correction for an infinite horizontal slab instead of a cap).

The Bouguer anomalies and all further relevant data of the gravity stations in the central Venezuelan Andes are shown in Table IV – 1. The

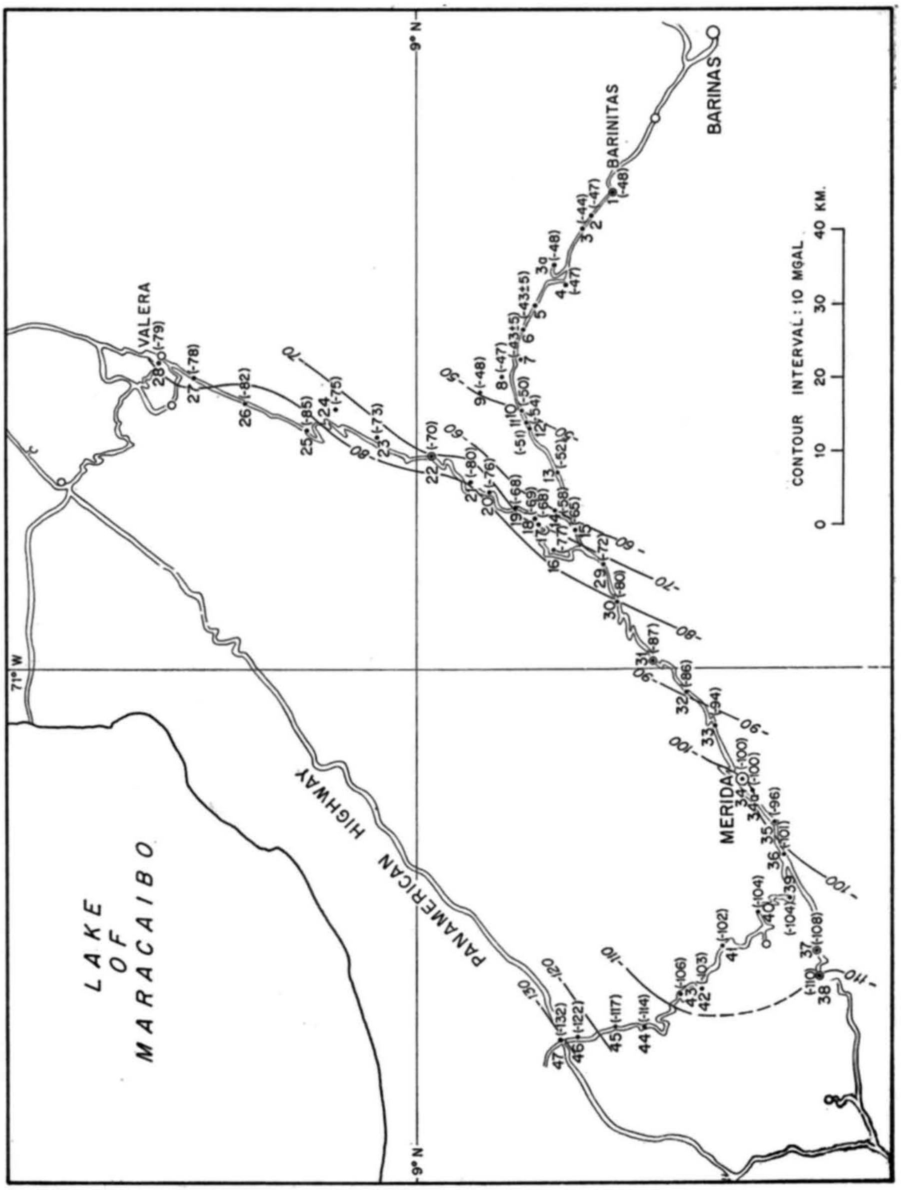


Fig. IV – 1. Bouguer anomalies for gravimeter stations in the Venezuelan Andes. Bouguer anomaly values (in mgal) are shown in brackets.

position of the gravity stations in shown in Fig. IV – 1. This figure also shows the number and Bouguer anomaly of each station.

In Fig. IV – 2 situation sketches are shown of four selected stations (Barinitas, Paramo de Mucuchies, Valera, and Merida). These sketches give the exact position of the gravity stations, as well as the observed values of gravity. They should be useful for connecting possible future surveys to the survey described in this account.

TABLE IV-1.

GRAVITY STATIONS IN THE CENTRAL VENEZUELAN ANDES

Station No.	Name	Longitude (W)	Latitude (N)	Height (m)	Method [1]	Observed gravity value (mgal)	Normal value of gravity [2] (mgal)	Lejay correction [3]	Topographical correction [4]	Bouguer anomaly [7] (mgal)
1	Barinitas.	70°24′ 25″	8°45′ 34″	528.3	M	978,012.53	978,168.4	103.2	4.3	−48
2	Cochinilla	70 26 10	8 46 52	615	B	977,994.61	169.0	120.2	7.4	−47
3	Barrangan	70 27 16	8 47 34	461	B	978,023.96	169.3	90.1	10.9	−44
3a	Altamira.	70 30 00	8 49 42	818	B	977,948.62	170.3	159.9	13.7	−48
4	Soledad	70 31 31	8 49 10	975	B	977,913.09	170.1	190.7	19.5	−47
5	San Isidro	70 32 44	8 50 54	999	B	906.34	170.9	195.4	[5]	[5]
6	Limite.	70 34 20	8 51 41	1343	B	832.50	171.2	262.8	33.3[6]	−43[6]
7	Capilla.	70 36 57	8 52 07	1560	B	774.20	171.4	305.4	48.9[6]	−43[6]
8	Las Piedras . . .	70 38 17	8 53 37	1717	B	764.28	172.1	336.3	24.9	−47
9	Pueblo Llano . .	70 39 29	8 55 03	2154	B	680.41	172.7	422.1	22.3	−48
10	Hotel Sto. Domingo	70 40 31	8 52 25	1986	B	707.18	171.6	389.2	25.3	−50
11	Sto. Domingo . .	70 41 50	8 51 46	2178.5	M	667.13	171.2	426.8	26.2	−51
12	F	70 42 10	8 51 29	2236	B	653.69	171.1	438.3	25.5	−54
13	A–1	70 45 49	8 49 19	2881	B	524.86	170.1	565.4	27.5	−52
14	A–2	70 48 10	8 49 35	3254	B	441.43	170.2	639.0	31.3	−58
15	Mucubaji	70 49 25	8 48 20	3577	B	379.86	169.7	702.8	22.1	−65
16	Rio Chama. . . .	70 51 21	8 49 54	3619	B	357.21	170.4	711.1	24.9	−77
17	Paramo	70 49 38	8 50 37	4044	M	280.15	170.7	795.3	27.7	−68
18	Verdun	70 49 02	8 50 41	3940	M	300.81	170.7	774.6	26.4	−69
19	X–1	70 48 20	8 52 09	3721	B	347.18	171.4	731.3	24.5	−68
20	Finca Montesana .	70 46 55	8 54 59	2962	B	488.60	172.7	581.3	27.0	−76
21	Chachopo	70 46 05	8 56 24	2587.3	M	558.01	173.4	507.4	27.6	−80
22	Timotes	70 44 19	8 59 10	1994.1	M	679.91	174.7	390.7	33.8	−70
23	Villa Mercedes . .	70 43 05	9 03 00	1510	B	778.67	176.4	295.6	28.7	−73
24	Rio Motatan . . .	70 40 46	9 05 52	1183	B	841.60	177.8	231.5	29.9	−75
25	La Puerta	70 42 17	9 08 04	1734	B	735.96	178.8	339.6	18.4	−85
26	Mendoza	70 39 56	9 12 46	1137	B	862.66	181.0	222.4	14.0	−82
27	Agua Clara. . . .	70 38 15	9 16 14	793	B	933.45	182.7	155.1	16.3	−78
28	Valera	70 36 45	9 18 47	549.0	(M)	990.26	183.9	107.3	7.2	−79
29	San Rafael. . . .	70 52 26	8 46 14	3102	B	462.56	168.7	609.0	25.2	−72
30	Mucuchies	70 55 10	8 44 54	2931	M	488.07	168.2	575.2	25.0	−80
31	Mucuruba	70 59 28	8 42 34	2370	M	582.94	167.0	464.6	32.4	−87
32	Cacute	71 02 17	8 39 16	1933	B	666.94	165.6	378.7	34.2	−86
33	Tabay.	71 04 41	8 38 01	1684	B	713.47	165.0	329.8	27.6	−94
34	Merida.	71 08 31	8 35 53	1598	M	731.55	164.1	312.9	19.6	−100
34a	Merida Airport . .	71 09 32	8 35 07	1497	B	751.63	163.8	293.1	19.2	−100
35	La Punta	71 11 53	8 33 37	1260	B	796.44	163.0	246.6	23.8	− 96
36	Egido	71 14 22	8 32 55	1137	B	818.30	162.8	222.4	20.7	−101
37	San Juan	71 21 23	8 30 31	1023	B	841.14	161.7	200.1	12.4	−108
38	Lagunillas	71 23 17	8 30 27	1048	B	834.15	161.7	205.0	12.9	−110
39	La Mesa	71 17 23	8 32 34	1393	B	770.90	162.6	272.7	15.4	−104
40	Las Cruces	71 18 36	8 34 40	1818	B	683.96	163.6	356.1	19.8	−104
41	La Sucia	71 20 57	8 37 07	2386	B	580.46	164.6	467.8	14.4	−102
42	X–2	71 24 03	8 39 08	2272	B	600.92	165.5	445.3	16.5	−103
43	X–3	71 24 56	8 40 46	1832	B	681.11	166.1	358.8	19.8	−106
44	La Azulita	71 26 37	8 42 59	1116	B	823.25	167.3	218.3	12.1	−114
45	Bolivia	71 26 44	8 45 23	671	B	977,905.28	168.4	131.2	14.8	−117
46	X–4	71 27 39	8 47 35	261	B	977,985.81	169.3	51.0	10.0	−122
47	Caño Zancudo . .	71 27 45	8 49 25	59.3	(M)	978,019.34	978,170.2	11.6	7.1	−132

REMARKS

1) M = bench mark, B = barometric levelling, (M) = existing gravity station.
2) Based on the 1930 International Formula.
3) Combination of correction for spherical plateau (density 2.67) and free-air correction (Lejay, 1947, Table III).
4) Zones $A–O_2$, density 2.67.
5) No reliable terrain correction could be made due to lack of sufficient topographic control in Zones F_1–H.
6) Terrain correction and hence anomaly uncertain by about 5 mgal. due to insufficient topographic control in Zones F_1–H.
7) Bouguer anomaly equals observed value minus normal value plus free-air correction minus spherical plateau (density 2.67) correction plus topographical correction (Zones $A–O_2$, density 2.67).

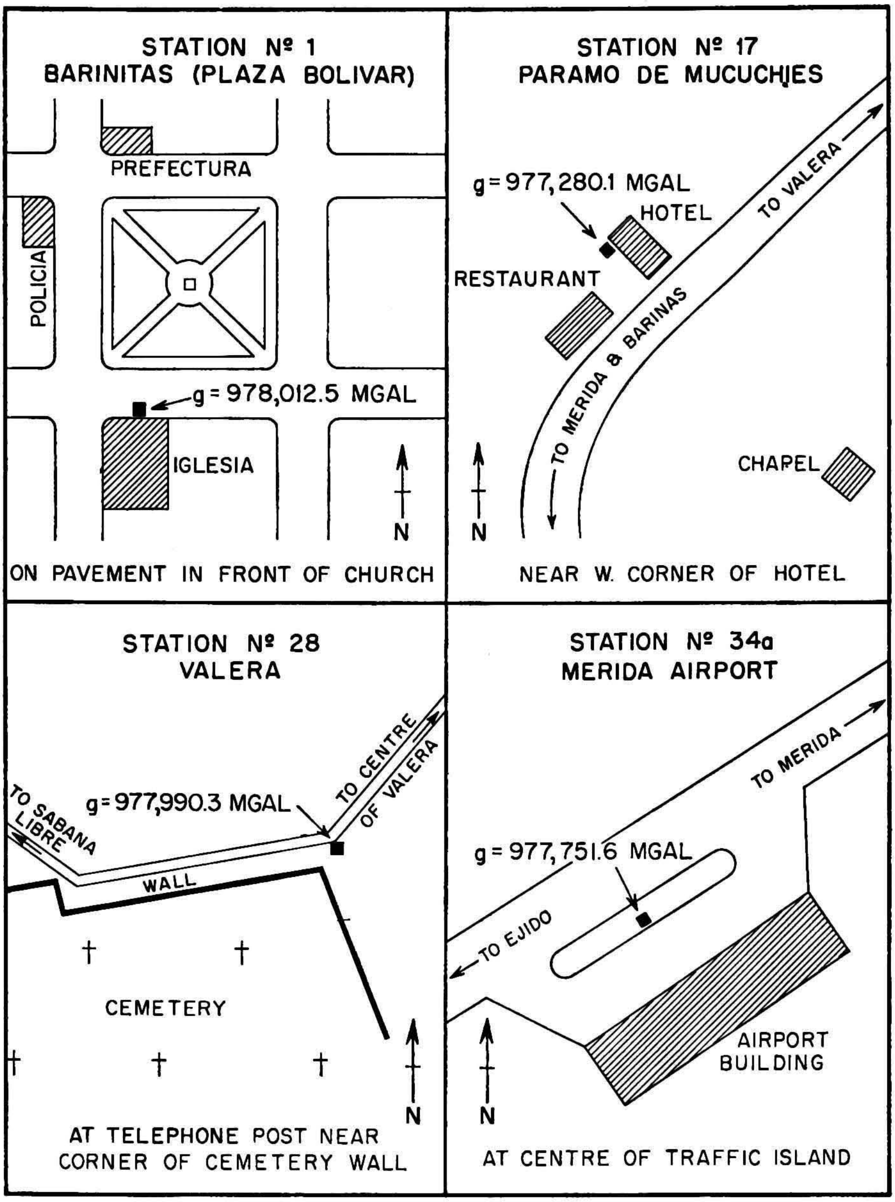


Fig. IV – 2. Situation sketches of four gravity stations with observed values of gravity, based on $g = 978{,}068$ mgal for the Shell gravity station in Caracas (situation sketches prepared by P. G. SLUITER).

f. *Bouguer anomaly map of the western part of Venezuela*

If a reliable Bouguer anomaly map of the western part of Venezuela is to be compiled, the conventional gravity survey results in the plains outside the Venezuelan Andes must be corrected for the terrain effect within Hayford's zones A–O_2 before they can be used in conjunction with the Andes survey results.

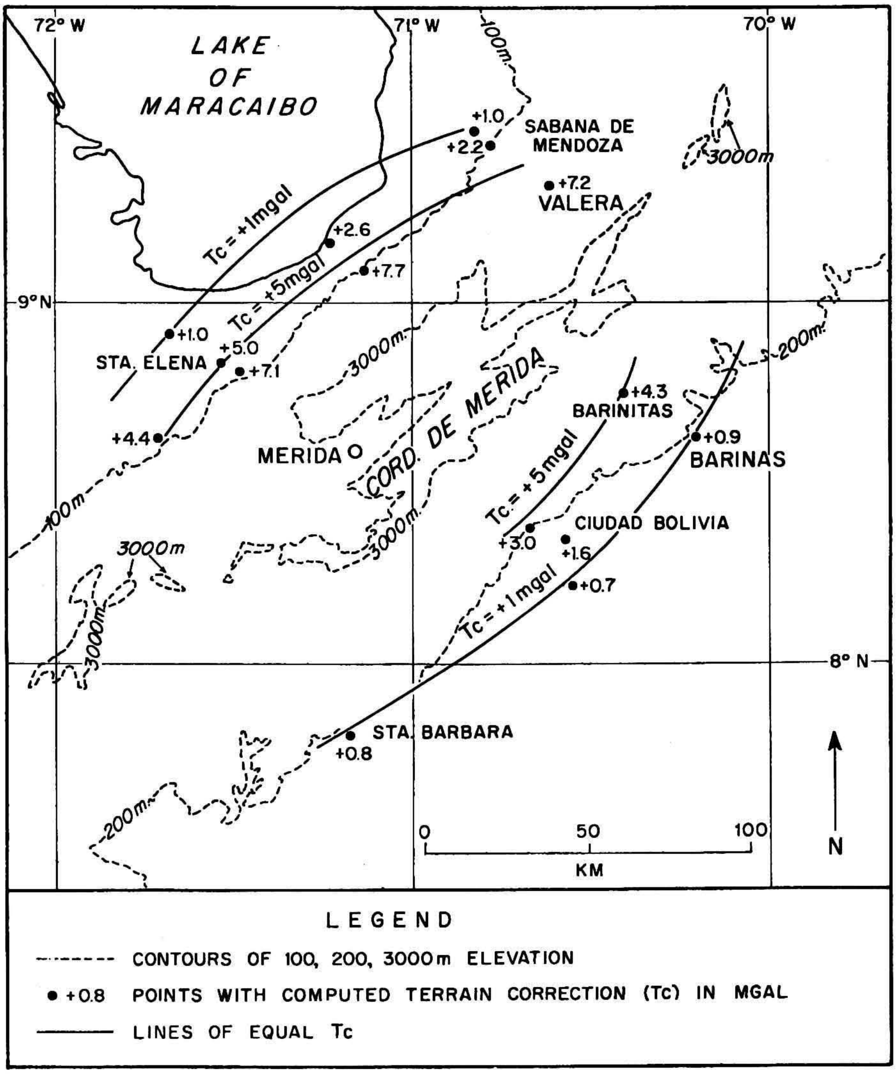


Fig. IV – 3. Topographical correction for Hayford's zones A–O_2 for stations outside the Venezuelan Andes.

Fig. IV – 3 shows the computed topographical corrections for a number of points outside the Andes, as well as some isocorrection lines based on these points. This topographical correction is, of course, computed in the same way as the topographical corrections in the Andes. It corrects for the effect of deviations of the existing topography from the spherical plateau of station height and extending to the outside of zone O_2. The density figure used is again 2.67.

Fig. IV – 3 shows that the topographical correction is far from negligible, and conventional gravity survey results in the areas adjoining the Venezuelan Andes have to be properly corrected before they can be incorporated in a compilation map.

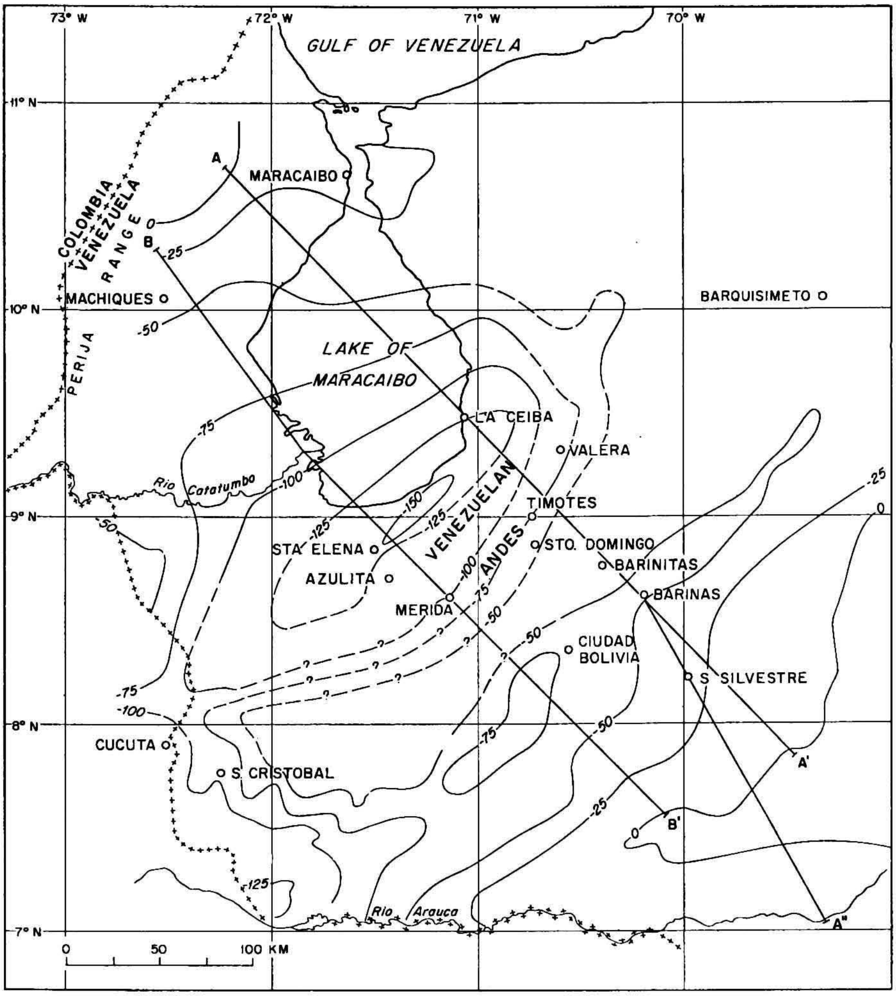


Fig. IV – 4. Bouguer anomaly map of western Venezuela. The contour interval i 25 mgal.

The compilation map (Fig. IV – 4) depicts Bouguer anomalies in western Venezuela contoured at intervals of 25 mgal. On this map the isogams have been smoothed somewhat in certain areas where the gravity field is known in much more detail than is actually shown. Smoothing, however, rarely exceeds 5 mgal.

The Bouguer gravity map, then, represents the gravity anomalies obtained by subtracting from the observed value of gravity the normal value of gravity according to the 1930 International Formula as well as the effect of a spherical plateau extending to the outer boundary of Hayford's zone O_2 (density 2.67 in the mountains, 2.1 in the plains). Added are the free-air correction and, where necessary, a topographical correction for zones A–O_2 and density 2.67. In practice, the spherical plateau correction for stations in the plains is replaced by the conventional

Bouguer correction. Due to the low elevations, the resulting error in the approximation is quite negligible.

Outside the Venezuelan Andes the gravity picture is well known, but in certain areas of the Venezuelan Andes, in particular in the mountain area south of Merida, the picture is incomplete. Some contours have been sketched in, but they must be considered as conjectural. A special expedition would be required to obtain gravity data in this area as all transport will have to be done on foot or by mule. Determinations of station heights will present a bigger problem than the actual gravity measurements, provided that a modern portable type of gravimeter is used.

V. ISOSTATIC CORRECTIONS

a. *Computation of isostatic corrections*

Eleven stations and selected points have been chosen for which isostatic corrections have been computed. Of these, five are situated in the Venezuelan Andes (gravimeter stations Nos. 1, 11, 25, 34 and 44), the others are selected points in the plains outside the Andes. Their position is shown in Fig. V – 1. They lie on the two gravity profiles A–A′ and B–B′, the position of which is also shown in Fig. IV – 4.

For each station isostatic corrections have been computed for 9 different systems of isostatic compensation. These systems are:

1) Systems of local compensation (Airy – Heiskanen hypothesis) for $T = 20$, 30 and 40 km ($R = 0$).

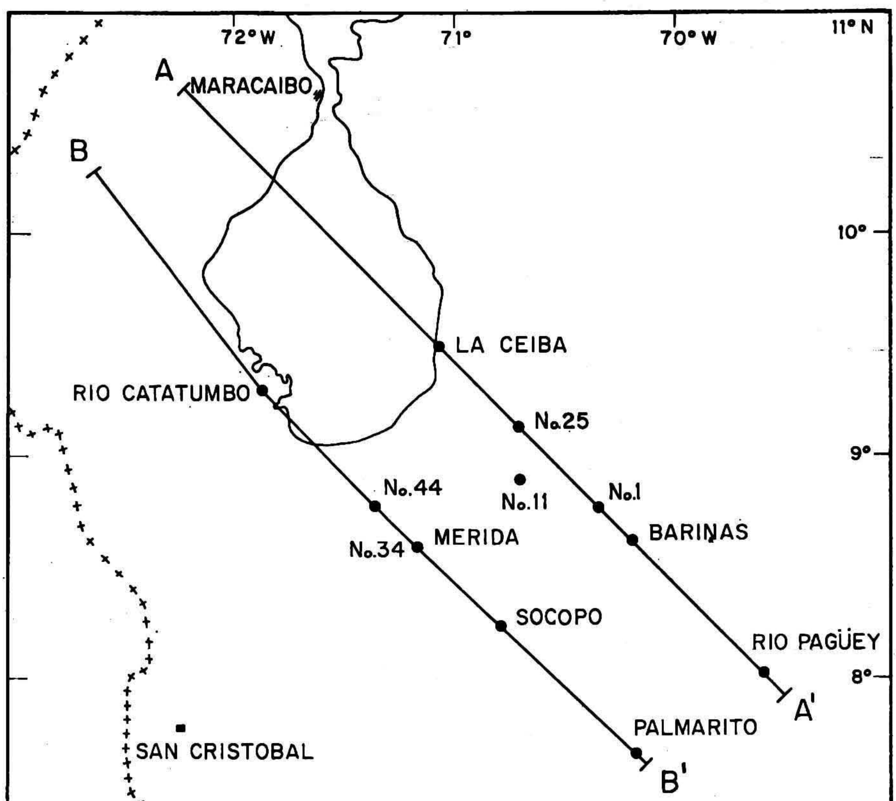


Fig. V – 1. **Location of stations and selected points for which isostatic corrections have been computed.**

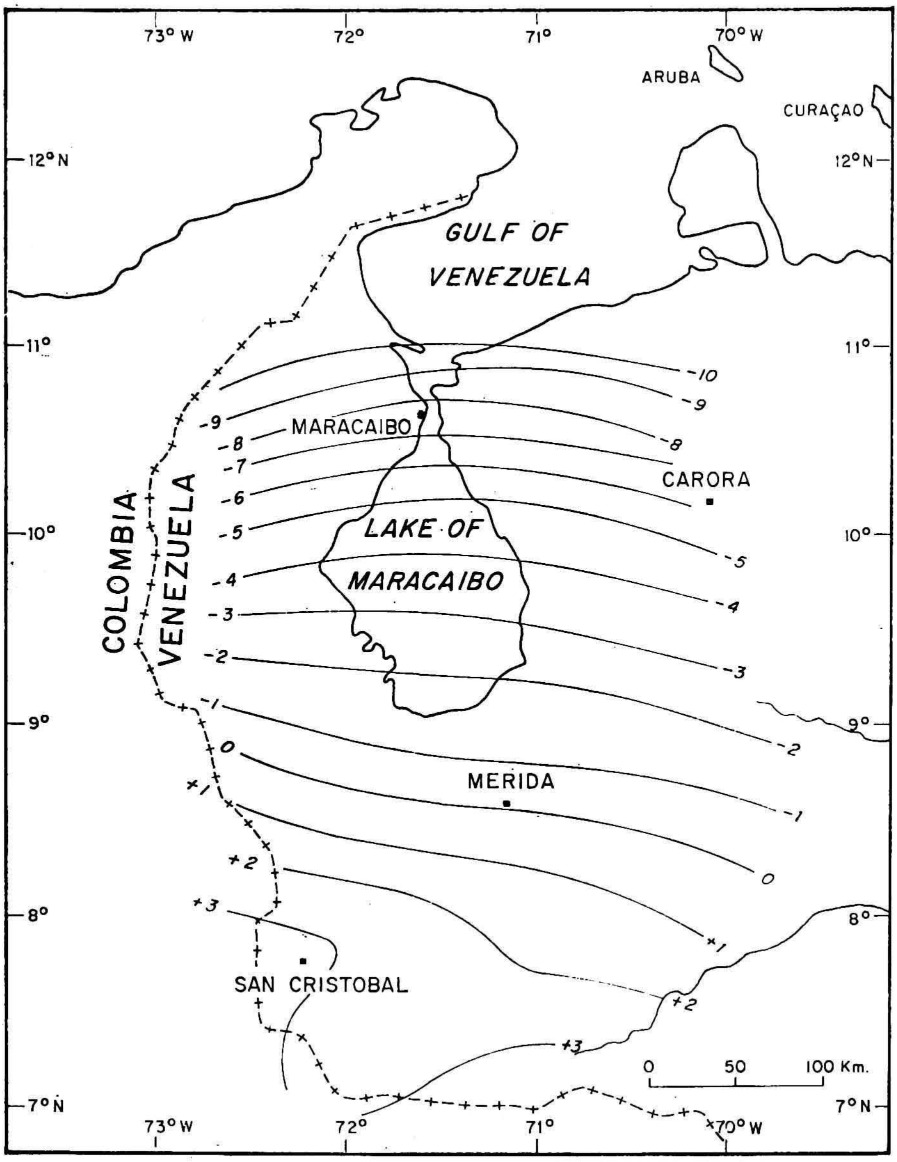


Fig. V – 2. Correction (in mgal) for the combined effect of topography and compensation of Hayford's zones 1–18 (T = 30 km, R = 0). Based on computations by L. L. MATTENS.

2) Systems of regional compensation according to Vening Meinesz for $R = 58.10$ and 232.40 km for each of the crustal thicknesses $T = 20$, 30 and 40 km.

For the computation of the effect of the isostatic compensation of the topography in zones A–O_2 Vening Meinesz's "Tables for regional and local isostatic reduction" (1941) have been used. The required height information for the stations in the Andes was obtained from that already recorded on the topographical correction data sheets. The maps used therefore are the same as those mentioned for the topographical

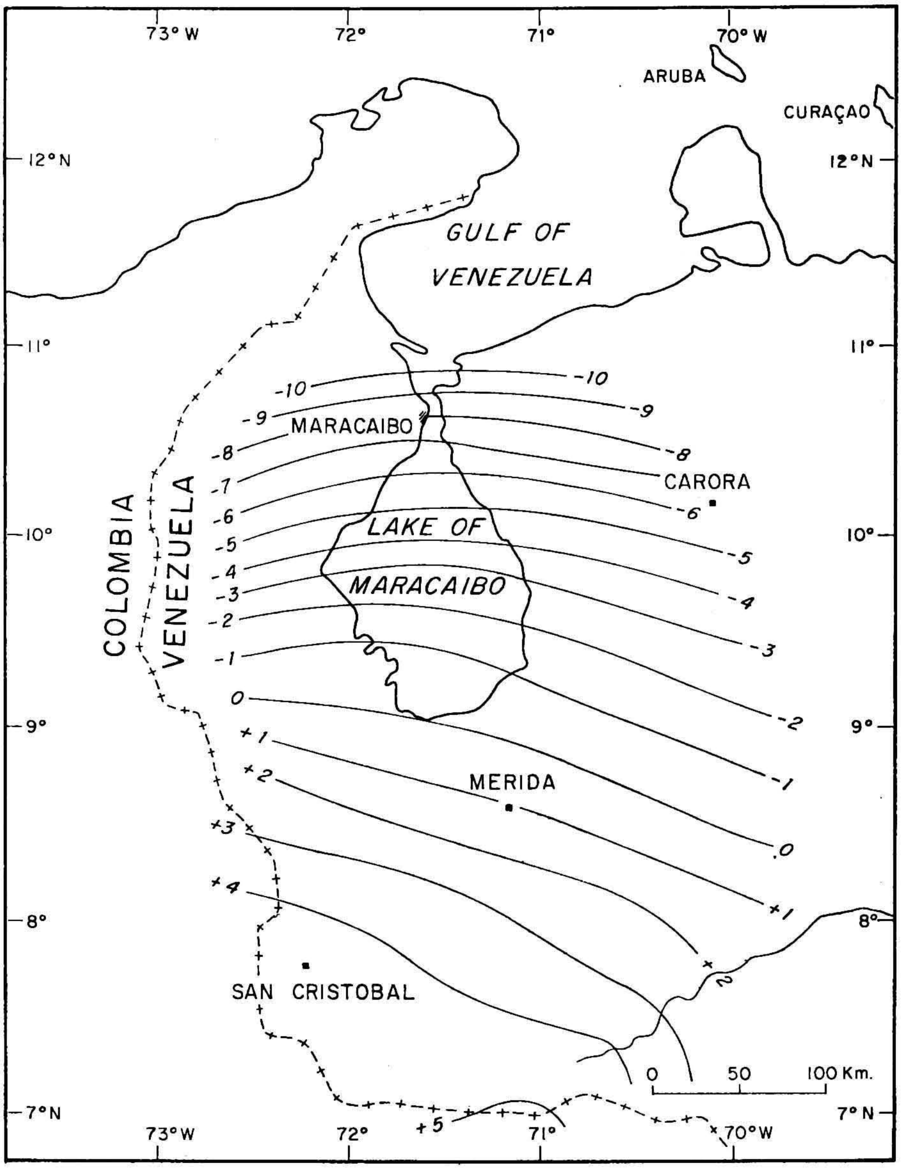


Fig. V – 3. Same (T = 30 km, R = 116.2 km).

corrections. The division into zones and compartments is also the same as that recommended by LEJAY (1947) for the topographical corrections. The only difference lies in the fact that for the isostatic corrections zones A–G are taken together and used as one zone. The average height for the combined zones A–G has been estimated from the 1:5,000 and 1:500,000 contour maps of the Venezuelan Andes listed in the preceding section. For points outside the Andes (not constituting part of the Andes gravity survey proper) heights in zones A–O_2 were estimated from the 1:500,000 and 1:1,500,000 contour maps already referred to.

The computation of the isostatic effect for each zone has been made somewhat more manageable by grouping compartment heights in groups of 0–1000, 1000–2000, 2000–3000, 3000–4000, and more than 4000 m height. The total effect of the zone

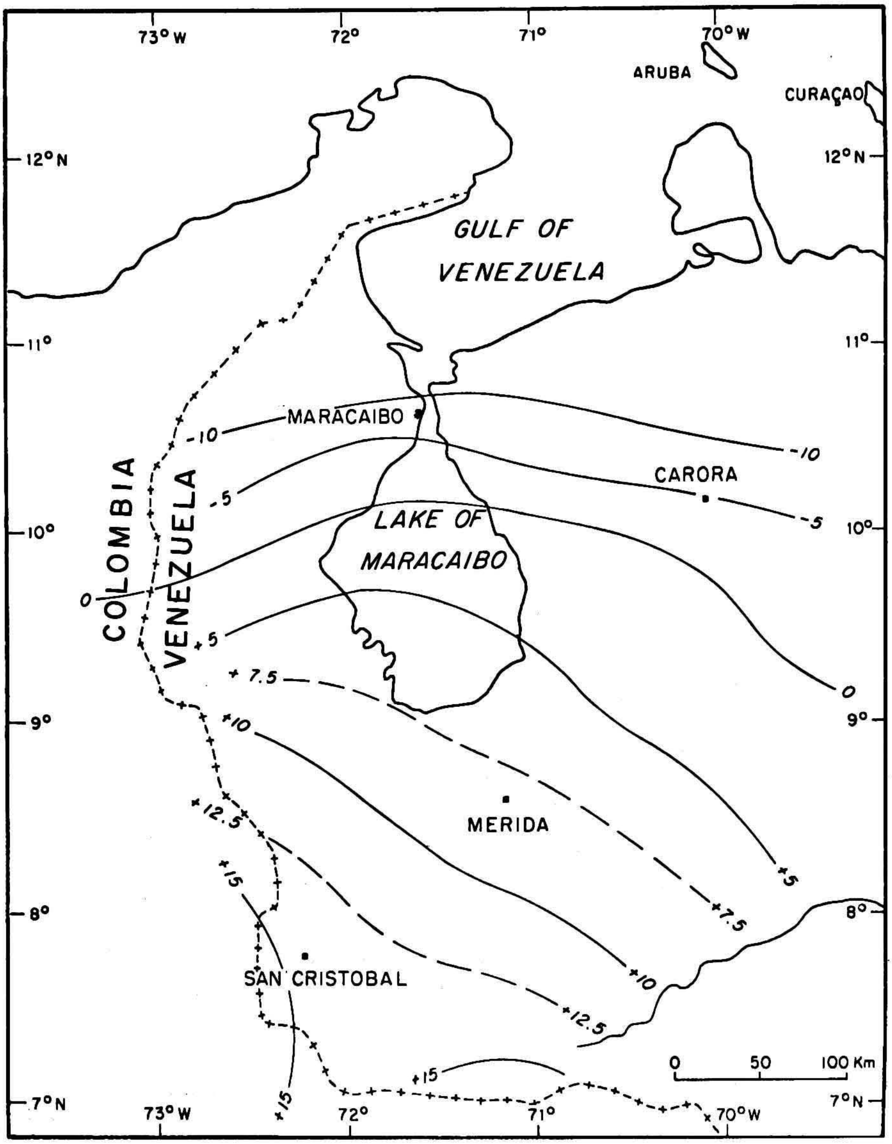


Fig. V – 4. Same (T = 30 km, R = 232.4 km).

is then computed by entering Vening Meinesz's tables with computed mean heights for these groups, and adding the values computed from the tables in a proper manner so as to allow for their proportional contribution. Only rarely could average elevations over the entire zone be used, and this was never done without estimating the error involved.

The computation of the effect of topography and compensation in zones 1–18 was fairly simple as Shell computations (carried out by L. L. Mattens) of this effect for T = 30 km combined with R = 0, 116.20 and 232.40 km were vailable. The following maps were used for these Shell computations:

1) The appropriate sheets of the 1:1,000,000 "Map of Hispanic America" published by the American Geographical Society of New York.

2) The "Carte Bathymétrique des Océans", (scale 1:10,000,000 at the equator) of the Bureau International Hydrographique at Monaco.
3) The "Bathymetric chart of the Caribbean Sea" of the U.S. Hydrographic Office (Scale about 1:3,000,000).
4) Heiskanen's "Topographic-isostatic world maps" for zones 1–10.

For the area of interest the correction for the combined effect of topography and compensation in Hayford's zones 1–18 is shown for $T = 30$ km and $R = 0$, 116.20, and 232.40 km in Figs. V - 2, V - 3 and V - 4 respectively. It will be noted that these maps show the correction, and not the effect which has the opposite sign.

From these data have been derived the corrections for zones 1–18 for the systems with $R = 0$, 58.10 and 232.40 km and $T = 20$, 30 and 40 km. This has been done guided by the following lines of reasoning:

1) $T = 30$, R = 0 and $R = 232.40$ can be taken from Figs. V - 2 and V - 4 respectively.
2) The correction for $R = 58.10$ is nearly the same as that for $R = 0$. This is true for each of the three values of T.
3) The correction for $T = 20$, $R = 0$ is 2/3 times the correction for $T = 30$, $R = 0$.
4) The correction for $T = 40$, $R = 0$ is 4/3 times the correction for $T = 30$, $R = 0$.
5) The correction for $R = 232.40$ is nearly the same for all three values of T.

These statements can be verified by comparing Figs. V - 2, V - 3 and V - 4, and by studying the table below of values taken from Vening Meinesz's tables (1941). This table (Table V - 1) shows the correction for a station at sea level for the combined effect (expressed in 0.1 mgal) of topography and compensation for zones 18–11 for an average zone elevation of 1000 m.

TABLE V - 1

Correction (in units of 0.1 mgal) for the combined effect of topography and compensation for zones 18–11 for an average zone elevation of 1000 m for a station at sea level.

Zone	$T = 20$ km			$T = 30$ km			$T = 40$ km		
No.	$R = 0$	58.10	232.40	$R = 0$	58.10	232.40	$R = 0$	58.10	232.40
18	17	18	90	23	25	86	29	31	83
17	16	17	80	22	23	80	28	29	79
16	15	16	55	21	22	63	27	28	68
15	15	16	33	21	22	43	27	28	52
14	14	14	23	20	20	32	26	27	40
13	22	22	29	31	31	41	41	42	53
12	13	13	15	19	19	22	25	25	28
11	10	10	11	15	15	16	19	19	21
SUM	122	126	336	172	177	383	222	229	424

N.B. All values are positive.

A third step in the calculation of the isostatic corrections is the correction for the elevation of the stations. This correction is only of interest for stations in the Andes. The topographical data used are the same as those used for the computation of the isostatic corrections. Here, however, average zone elevations can be employed. Corrections of less than 1 mgal have been neglected altogether. The elevation correction has been restricted to zones A–O_2.

TABLE V - 2.

ISOSTATIC CORRECTIONS

NAME					T = 20 km							
OF	R = 0				R = 58.10				R = 232.40			
STATION	I	II	III	IV	I	II	III	IV	I	II	III	IV
Rio Pagüey. . .	+ 17.3		+1.0	+ 18	+ 17.7		+1.0	+ 19	+22.7		+9.0	+32
Barinas	+ 46.9		—0.7	+ 46	+ 54.7		—0.7	+ 54	+44.7		+5.2	+50
Barinitas (1) . .	+ 86.4		—0.8	+ 86	+ 90.7		—0.8	+ 90	+51.1		+5.0	+56
Sto. Domingo (11)	+155.2	—6.9	—0.8	+147	+130.1	—5.3	—0.8	+124	+55.9	—1.3	+5.8	+60
La Puerta (25) .	+139.2	—4.2	—1.3	+134	+124.3	—3.5	—1.3	+119	+58.4	—0.9	+4.5	+62
La Ceiba	+ 28.1		—2.0	+ 26	+ 35.9		—2.0	+ 34	+38.1		+4.5	+43
Palmarito . . .	+ 17.3		+1.0	+ 18	+ 17.7		+1.0	+ 19	+22.7		+9.0	+32
Socopo	+ 73.4		+0.5	+ 74	+ 82.1		+0.5	+ 83	+52.5		+8.5	+61
Merida (34). . .	+155.4	—5.4	0.0	+150	+131.5	—3.9	0.0	+128	+52.1	—0.8	+8.2	+60
La Azulita (44) .	+106.5	—1.0	—0.7	+105	+102.1	—1.2	—0.7	+100	+52.9	—0.6	+7.6	+60
Rio Catatumbo .	+ 9.6		—1.5	+ 8	+ 11.3		—1.5	+ 10	+30.0		+6.5	+36

NAME					T = 30 km							
OF	R = 0				R = 58.10				R = 232.40			
STATION	I	II	III	IV	I	II	III	IV	I	II	III	IV
Rio Pagüey. . .	+ 17.4		+1.5	+ 19	+ 17.8		+1.5	+ 19	+21.3		+9.0	+30
Barinas	+ 48.8		—1.0	+ 48	+ 53.4		—1.0	+ 52	+40.9		+5.2	+46
Barinitas (1) . .	+ 80.7		—1.2	+ 80	+ 80.9		—1.2	+ 80	+46.5		+5.0	+51
Sto. Domingo (11)	+124.6	—5.3	—1.2	+118	+108.4	—4.4	—1.2	+103	+50.1	—1.2	+5.8	+55
La Puerta (25) .	+115.8	—3.2	—2.0	+111	+105.5	—2.7	—2.0	+101	+52.5	—1.0	+4.5	+56
La Ceiba	+ 32.6		—3.0	+ 30	+ 37.9		—3.0	+ 35	+35.0		+4.5	+40
Palmarito . . .	+ 17.4		+1.5	+ 19	+ 17.8		+1.5	+ 19	+21.3		+9.0	+30
Socopo	+ 73.5		+0.8	+ 74	+ 77.3		+0.8	+ 78	+49.5		+8.5	+58
Merida (34). . .	+124.5	—4.2	0.0	+120	+109.7	—2.9	0.0	+107	+46.4	—0.9	+8.2	+54
La Azulita (44) .	+ 93.9	—1.0	—1.0	+ 92	+ 89.6	—1.2	—1.0	+ 87	+52.6	—0.6	+7.6	+60
Rio Catatumbo .	+ 12.5		—2.2	+ 10	+ 14.5		—2.2	+ 12	+28.0		+6.5	+34

NAME					T = 40 km							
OF	R = 0				R = 58.10				R = 232.40			
STATION	I	II	III	IV	I	II	III	IV	I	II	III	IV
Rio Pagüey. . .	+ 17.3		+2.0	+19	+17.6		+2.0	+20	+19.6		+9.0	+29
Barinas	+ 47.9		—1.3	+47	+50.4		—1.3	+49	+37.2		+5.2	+42
Barinitas (1) . .	+ 73.0		—1.6	+71	+72.0		—1.6	+70	+42.2		+5.0	+47
Sto. Domingo (11)	+102.5	—4.0	—1.6	+97	+91.8	—3.5	—1.6	+87	+45.4	—1.1	+5.8	+50
La Puerta (25) .	+ 98.3	—2.3	—2.7	+93	+90.9	—1.9	—2.7	+86	+49.2	—1.0	+4.5	+53
La Ceiba	+ 34.4		—4.0	+30	+37.6		—4.0	+34	+32.6		+4.5	+37
Palmarito . . .	+ 17.3		+2.0	+19	+17.6		+2.0	+20	+19.6		+9.0	+29
Socopo	+ 69.2		+1.1	+70	+70.3		+1.1	+71	+43.8		+8.5	+52
Merida (34). . .	+102.1	—3.0	0.0	+99	+90.9	—2.4	0.0	+89	+42.7	—1.0	+8.2	+50
La Azulita (44) .	+ 82.0	—1.0	—1.3	+80	+77.9	—1.0	—1.3	+76	+53.5	—0.4	+7.6	+61
Rio Catatumbo .	+ 14.9		—2.9	+12	+16.6		—2.9	+14	+26.0		+6.5	+32

LEGEND. Number between brackets after station name is number of gravity station in the Venezuelan Andes.

Column headings: I = Isostatic correction zones A–O_2
II = Correction for elevation of station*
III = Isostatic correction zones 18–1 (topography plus compensation)
IV = Total Isostatic correction

} in mgal.

* Not shown if less than 1 mgal.

The isostatic corrections for the selected eleven stations and points for $T = 20$, 30 and 40 km, each for $R = 0$, 58.10 and 232.40 km, are shown in table V – 2. They have been shown separated into their component parts:

1) correction for effect of compensation in zones A–O_2.
2) correction of preceding item for elevation of station.
3) correction for combined effect of topography and compensation for zones 1–18.

These three corrections added together, observing their signs, give the isostatic corrections.

b. *Accuracy of Bouguer anomalies and isostatic corrections*

The final accuracy of the Bouguer anomalies is largely determined, in the case of stations in the central Venezuelan Andes, by the uncertainties in the altitude and in the topographical corrections. The resulting uncertainty in the Bouguer anomalies, due to the former cause, is of the order of 1 to 1½ mgal. That due to the latter cause is usually less than 1½ mgal, except for stations No. 5, 6, and 7 (cf. Table IV – 1). Apart from these three stations, the uncertainties in the Bouguer anomalies are therefore negligible compared with the magnitude of the Bouguer anomalies.

For the Bouguer anomalies in areas outside the Venezuelan Andes, the uncertainties are practically exclusively caused by the smoothing applied to them. This smoothing rarely exceeds 5 mgal. The Bouguer anomalies computed for the Holweck-Lejay pendulum stations in the Tachira area, however, are less accurate. As they have only been used for the preparation of the compilation map, this low accuracy is of no further interest.

The isostatic corrections are inaccurate because of an uncertainty of 1–2 mgal in the correction for zones 1–18, an uncertainty of not more than 1 mgal in the elevation correction, and an uncertainty of several mgal in the correction for zones A–O_2. The largest isostatic corrections may therefore be uncertain by 5 mgal or so.

VI. DISCUSSION OF RESULTS

a. *Bouguer anomalies*

The Bouguer anomaly map of the western part of Venezuela (Fig. IV - 4) shows a pronounced minimum of -150 mgal (the so-called Sta. Elena minimum) to the northwest of the Venezuelan Andes, and a minimum of lesser magnitude (-75 mgal) on the opposite side of the Andes. In the Venezuelan Andes the Bouguer anomalies form a relative maximum of about -50 mgal. In its essentials, therefore, the gravity field of Western Venezuela is very simple.

In Fig. VI – 1 two profiles of Bouguer anomalies are shown. The position of these profiles is shown in Figs. IV – 4 and V – 1. On profile A–A′ a part of the profile between La Ceiba and La Puerta is conjectural, but cannot be much different from that shown. On profile B–B′ a part southeast of Merida is conjectural. It is known, however, that on both sides the Bouguer anomaly increases towards this part of the profile. The conjectural Bouguer anomalies are therefore probably not very different from the true ones.

The significance of Bouguer anomalies in a case like the present one is two-fold. Firstly, they are an intermediate step in the calculation of isostatic anomalies. Secondly, they represent, to an extent to be specified immediately below, the effect of the mass-irregularities (i.e., lateral density changes) below sea level in which we are interested in this investigation. Mass-irregularities above sea level (i.e., deviations from the uniform density assumed) will also be reflected in the Bouguer anomalies, but unless there is evidence to the contrary, one may safely assume that these effects are non-existent or negligible.

The Bouguer anomalies, then, represent the effect of mass-irregularities below sea level and inside a circle of 166.7 km radius (outer radius of Hayford's zone O_2), as well as the combined effect of topography and compensation of the rest of the earth. These effects are measured at station height.

The effect of topography plus compensation outside zone O_2 is nearly negligible for $R=0$ and $R=58.10$ km for all three crustal thicknesses ($T=20$, 30 and 40 km). For the largest degree of regionality it is, however, not negligible (Table V – 2, Fig. V – 4). The main difficulty, however, if it is decided to correct for the effect of topography and compensation in zones 1–18, is to decide which system of isostatic compensation has to be used.

Here, the system of local isostatic compensation ($R=0$) for $T=30$ km has been chosen. This choice has been guided by the consideration that this system is probably nearest the truth and that corrections applied

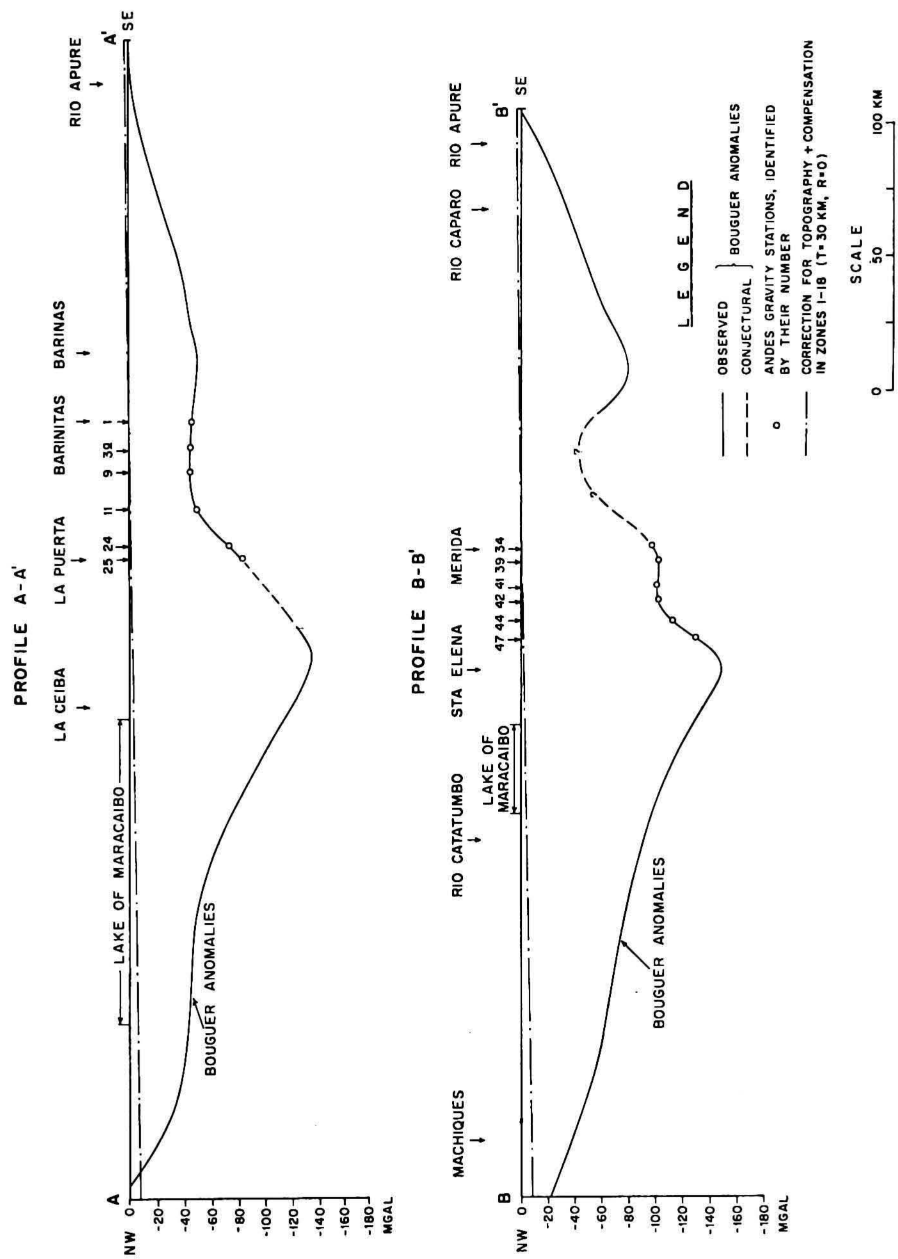


Fig. VI – 1. Bouguer anomaly profiles of the Venezuelan Andes and adjacent basins.

according to this system probably give better data than the uncorrected ones. However, it is fully realised that this choice remains somewhat arbitrary.

The correction is shown in Fig. VI – 1. By adding it to the Bouguer anomalies an anomaly is obtained which was first introduced by VENING

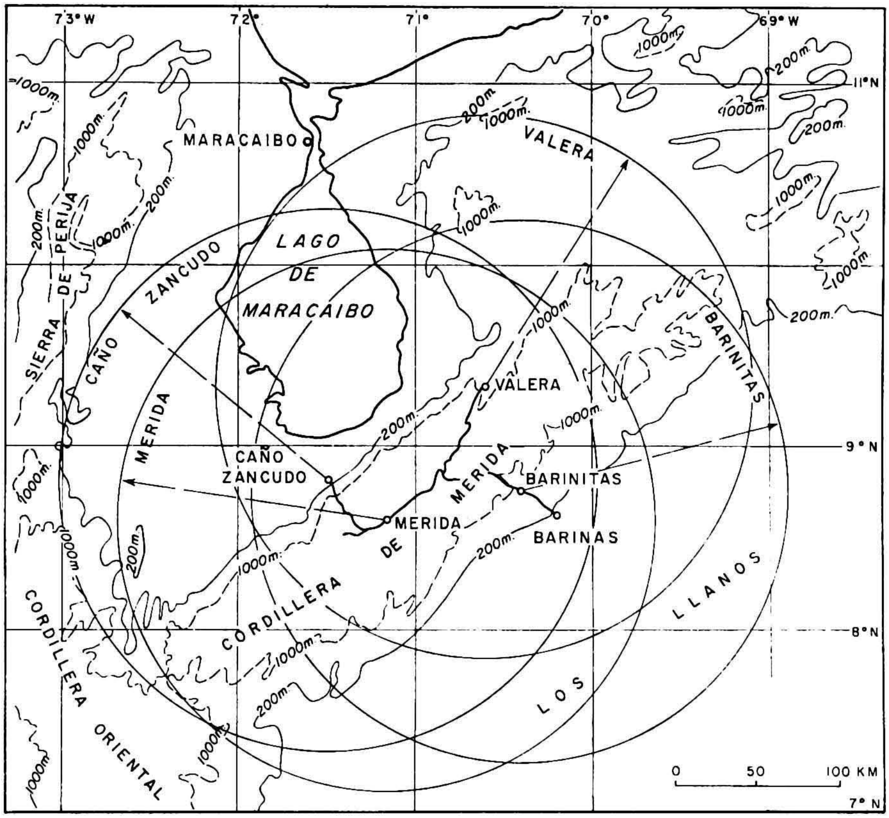


Fig. VI – 2. Map of the western part of Venezuela and a part of Colombia, showing a few selected gravity stations with circles representing the outer boundary of zone O_2 (radius 166.7 km).

MEINESZ (1934) and to which he has given the name of "Modified Bouguer Anomaly".

It should be pointed out that if the topography in zones 1–18 is not or only partly compensated, or if it is overcompensated, or if both under- and over-compensation occur, errors must result. Fortunately, such errors may be expected to be small.

Station height is of importance only for stations Sto. Domingo, La Puerta and Merida (cf. Table V – 2) and then only in a limited number of systems of isostatic compensation. For preliminary computations of the effect of assumed mass distributions one may therefore safely disregard the effect of station height. For more accurate computations it is a simple matter to take the effect of station height into account, as has in fact been done in all computations in this investigation.

It may be of interest to see on a map just how far the outside of zone O_2 reaches. This is shown in Fig. VI – 2 for a few gravity stations in the Andes.

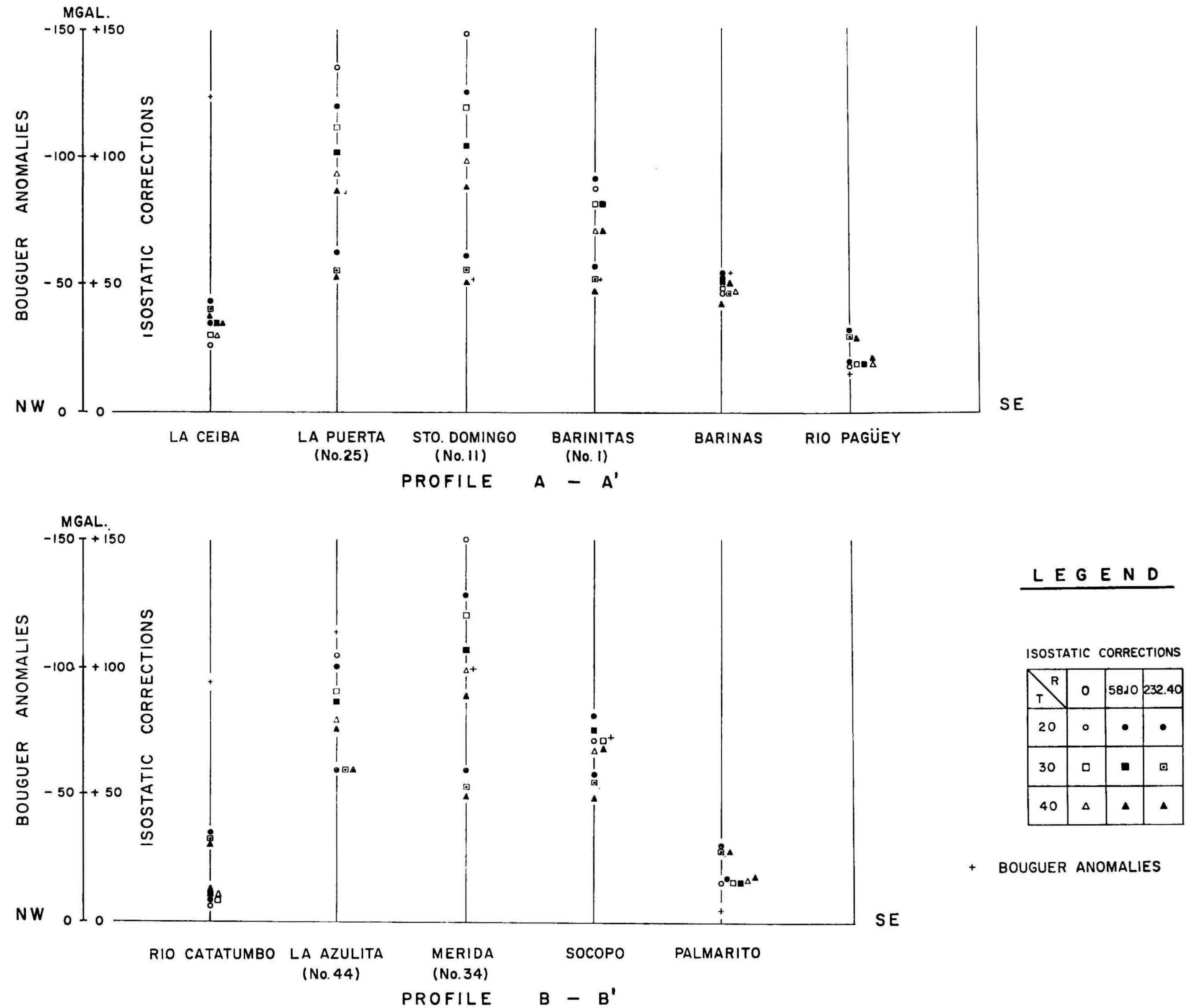


Fig. VI – 3. Diagram for comparison of Bouguer anomalies and isostattic corrections.

b. *Isostatic anomalies*

Isostatic anomalies are obtained by adding the isostatic corrections to the Bouguer anomalies. In Fig. V – 1 are shown the stations for which isostatic corrections have been computed; the corrections themselves are shown in table V – 2.

Isostatic corrections serve the purpose of testing a hypothesis. The hypothesis in the present case is that the topography in general, and in particular the visible extra masses of Andes topography above sea level, are compensated by equivalent mass deficiencies below sea level. Different systems of isostatic compensation differ in the assumptions they make about the depth at which the compensating masses, if present, are situated, and the manner in which these masses are distributed in a lateral direction.

The best system of isostatic compensation is that which produces the smoothest isostatic anomalies. The smoothness can be tested, for example, by computing the mean of the squares of the deviations of individual isostatic anomalies from the mean isostatic anomaly (the mean isostatic anomaly need not necessarily be zero). This quantity is a minimum for the best system.

However, it may be pointed out that the best system of isostatic compensation need not necessarily be the same for groups of observations in, say, mountain areas and basins, nor need it be the same in different parts of the same mountain range. The inspection of isostatic anomalies in such instances (and the western part of Venezuela appears to be one such instance) had therefore better proceed along somewhat different lines.

The procedure chosen here is to compare the magnitude of the Bouguer anomalies of a selected number of stations with the computed isostatic corrections. This comparison is made in Fig. VI – 3. This is a diagram comparing for each of the two profiles A–A′ and B–B′ (cf. Figs. IV – 4 and V – 1) the observed Bouguer anomalies with the isostatic corrections. It will be noted that the stations in reality are not uniformly spaced as Fig. VI – 3 might suggest.

Inspection of Fig. VI – 3 shows that stations in the plains have no diagnostic value as the isostatic corrections for the nine different systems are very nearly the same. This is particularly true for stations Rio Pagüey, Barinas, La Ceiba, and Palmarito, and it is true to a slightly lesser extent for stations Socopo and Rio Catatumbo.

It is also evident that the Bouguer anomalies of La Ceiba and Rio Catatumbo cannot be reduced by even as much as 40 % by the isostatic corrections. It is to be noted that no such pronounced effect exists in the Barinas-Apure Basin.

For the stations in the Andes it appears that there is no single system of isostatic compensation that makes all anomalies zero or, at least, much smaller in magnitude than the observed Bouguer anomalies. The comparison suggests that for stations Barinitas and Sto. Domingo systems of pronounced regional compensation ($R = 232.40$ km) are the best ones. For stations La Puerta, Merida, and La Azulita, on the other hand, a high degree of regionality is out of the question. Isostatic compensation is imperfect in any case for these stations, but it would seem that *R* lies somewhere between 0 and 58.10 km. *T* is indeterminate but if a common *T* is to be used for these stations, $T = 30$ km is probably the best value.

The conclusions to be drawn at this stage from the isostatic anomalies are therefore:

1) There is no system of isostatic compensation common to all stations.
2) In the Maracaibo Basin there is an additional gravity deficit. The Barinas-Apure Basin does not exhibit this feature to the same degree.
3) In the Venezuelan Andes there seems to be pronounced regional compensation in the southeastern range, and local or weak regional compensation in the northwestern range.

c. *The Maracaibo Basin*

For a proper discussion of the gravity field of a basin such as the Maracaibo Basin, extensive and reliable density information would be required in order to reach well-founded conclusions concerning the gravity effect of the sedimentary basin fill. Unfortunately, the reliability of the available data is not sufficient to do so and a somewhat lengthy discussion is therefore necessary in order to isolate the information that can be used.

The amount of information on the density of sediments in the Maracaibo Basin is fairly extensive. The density values available are the result of specific gravity determinations of well cores, carried out in the laboratory by means of a specific gravity balance. This method allows densities to be determined quickly and accurately to within 0.01 g/cm^3.

Routine density determinations on well cores, however, have some serious disadvantages, namely that loss of original pore liquid of cores may easily occur during transport and storage, and that the process of coring itself may conceivably influence the density of the core. The available density information must therefore be used with great caution. There is, in addition, the possibility that the sampling has been biassed, for practical reasons, towards sediments of one particular type. The samples are then no longer truly representative of the sedimentary column in the well.

In this connection an investigation by HAMMER (1950) is of direct interest. In this investigation density measurements on selected core drill rock samples were compared with the densities determined from gravity observations in a vertical mine shaft. It was found that the individual sample measurements show large scatter and yeild systematically lower values than those derived from the gravity measurements. As significant sources of systematic error in the gravity measurements have not been found in this very careful investigation, HAMMER concludes that the discrepancies probably must be ascribed to drying or other changes (possibly associated with the core drilling itself) in the samples.

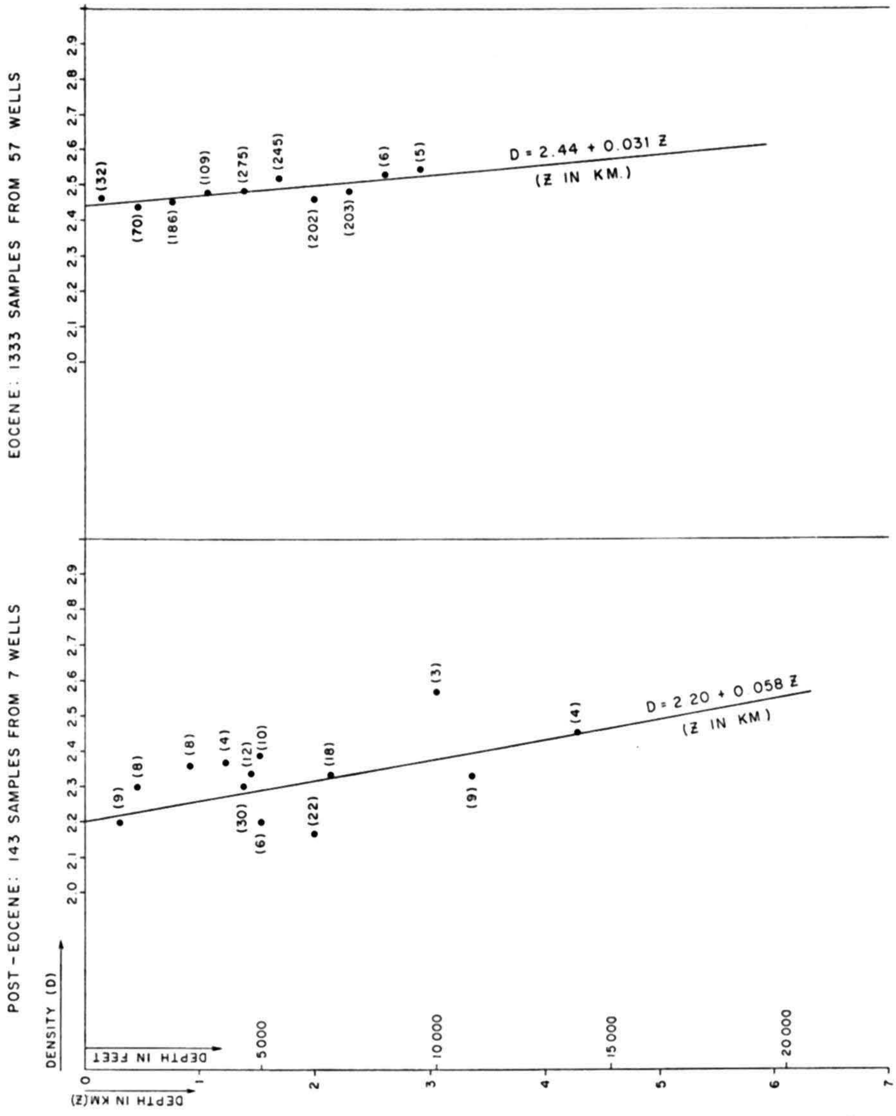


Fig. VI – 4. Density-depth relations in the Maracaibo Basin. Between brackets is shown the number of samples which each point represents (based in part on data collected by J. Carr).

The density information for the Maracaibo Basin has been divided according to the geological age of the sediments. There are a sufficient number of density determinations for Post-Eocene, Eocene, and Cretaceous sediments.

Post-Eocene sediments:

Fig. VI – 4 shows the average density of groups of determinations (the number of determinations is shown in the figure) plotted against depth. In total there are 143 samples, taken from 7 wells in the Maracaibo

Basin. The theoretical straight line has been found by dividing the observations into two groups (below and above 3000 m depth), determining the centre of gravity of each group (duly allowing for the different weights of the groups of observations) and connecting the two centres of gravity. The equation of this straight line is

$$D = 2.20 + 0.058\,Z \ \text{g/cm}^3$$

where D is the density and Z the depth in km.

Eocene sediments:

In Fig. VI – 4 a similar plot is also shown for Eocene sediments. This figure is based on 1333 samples from 57 wells in the Maracaibo Basin. The straight line has been found by the method of least squares, assigning equal weight to all groups. The equation of the straight line is

$$D = 2.44 + 0.031\,Z \ \text{g/cm}^3$$

where D is the density and Z the depth in km.

Not included are density determinations of Eocene cores from wells in the Bolivar Coast area. The Eocene densities of the Bolivar Coast area are known to be significantly higher than Eocene densities elsewhere in the Maracaibo Basin. Representative figures for the Maracaibo Basin are therefore probably more easily obtained by excluding data from this abnormal area.

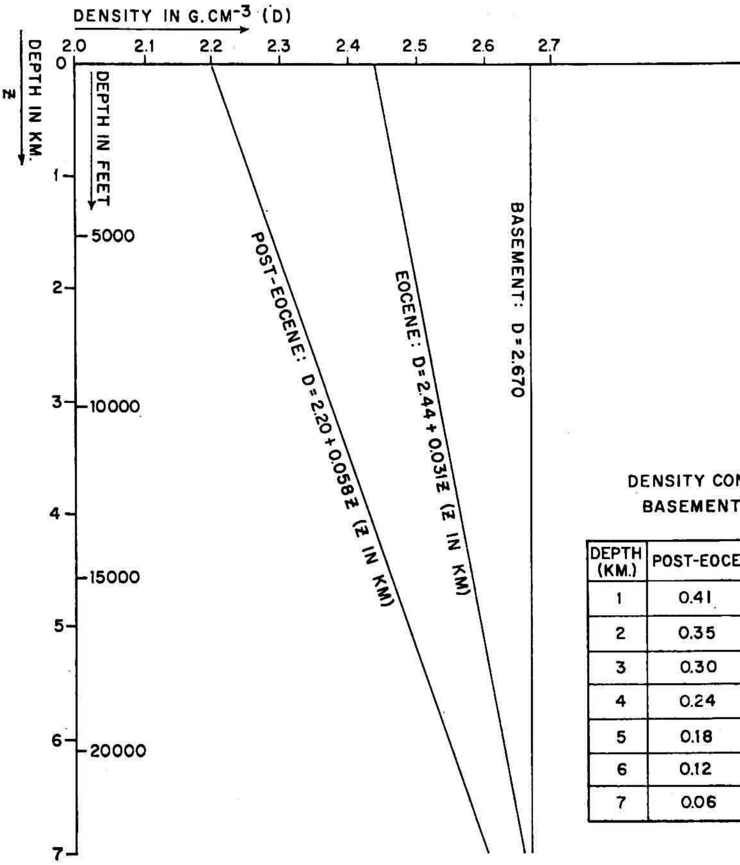
Cretaceous sediments:

Information on the density of Cretaceous cores is not extensive. The available data show that possible deviations of the average density of the Cretaceous sediments from the basement density are so small that no significant gravity effect will arise from it.

Basement:

A basement density of 2.670 has been used here for the assessment of the density contrast between sediments and basement. This is not only a figure commonly used, but it is also the best figure resulting from a study of rock densities in the central Venezuelan Andes (HOSPERS and VAN WIJNEN, 1958). In that study it was found that neither the mean density of all samples nor the mean of the samples of igneous and metamorphic rocks differ significantly from 2.670.

The use of straight lines to represent the increase of density with depth may call for comment. ATHY (1930) has related density and depth of shales by an exponential function, a type of function which also seems quite adequate to represent density-depth data published by HEDBERG (1936). However, the data shown in Fig. VI – 4 do not seem to justify a more refined representation than straight lines. For that reason, we shall first accept these theoretical density-depth relations, and later consider possible objections against them.



DENSITY CONTRAST WITH BASEMENT IN G/CM^3

DEPTH (KM.)	POST-EOCENE	EOCENE
1	0.41	0.20
2	0.35	0.17
3	0.30	0.14
4	0.24	0.11
5	0.18	0.08
6	0.12	0.04
7	0.06	0.01

Fig. VI – 5. Density-depth relations used for the computation of the maximum effect of light sediments in the Maracaibo Basin.

If the preceding density-depth relations (Fig. VI – 5) are to be used for a calculation of the gravity effect, the Post-Eocene relationship should only be applied to Post-Eocene sediments, and the Eocene relation only to Eocene sediments. This is not convenient, however, as published data on thicknesses and depths refer to Top Eocene and Top Cretaceous Limestone. For that reason the relation for Eocene sediments has to be extended downwards to cover Paleocene and Cretaceous (Senonian) sediments above the Cretaceous Limestone as well. The error thus introduced is insignificant.

The depth information on Top Eocene and Top Cretaceous Limestone is shown in Fig. VI – 6 (after MILLER *et al.*, 1955). From this map, profiles across the Maracaibo Basin have been constructed. These profiles coincide with our gravity profiles A–A′ and B–B′; their position is shown in Fig. VI – 6. The profiles themselves are shown in Fig. VI – 7. From the data on thicknesses and density contrasts shown there the gravity effect has been computed. It will be noted that the average density contrast between the sedimentary fill above the Top Cretaceous Limestone and the basement varies between -0.19 and -0.27 g/cm^3. This is more

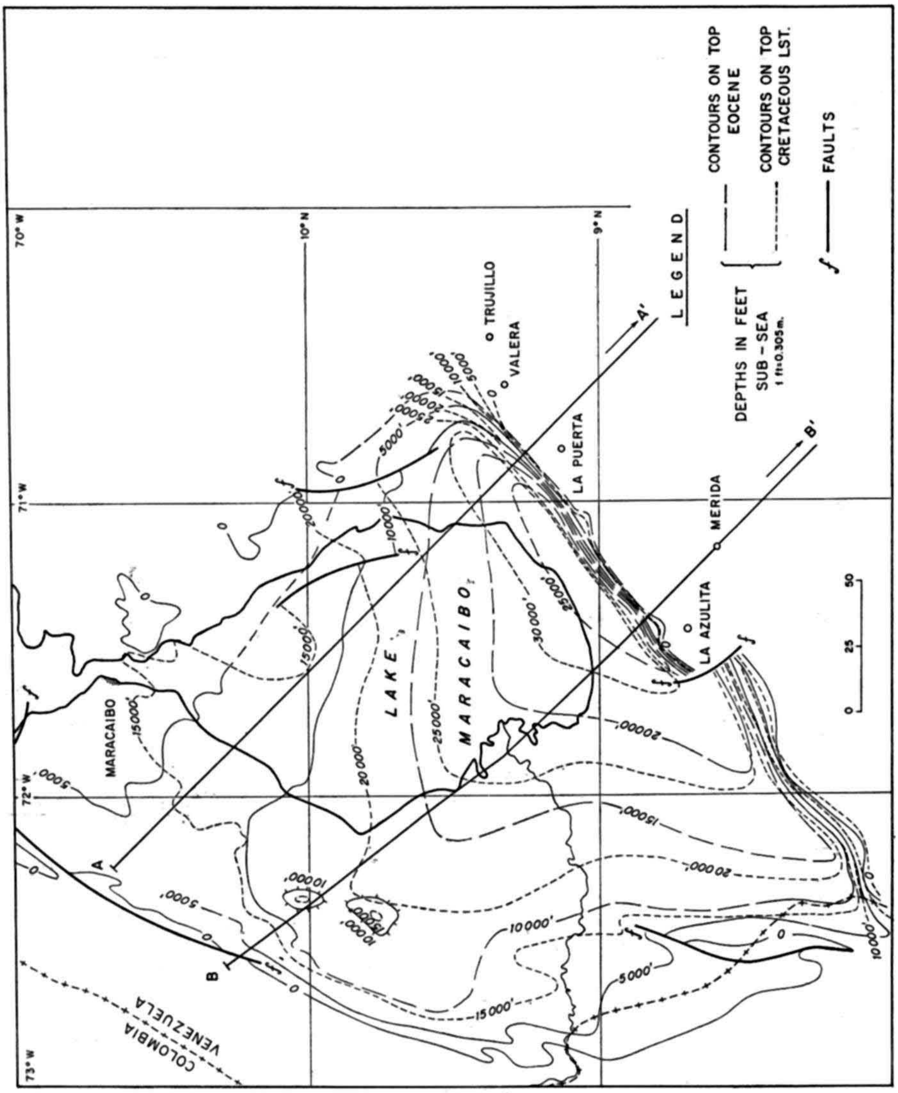


Fig. VI – 6. Depth in feet below sea level of Top Eocene and Top Cretaceous Limestone in the Maracaibo Basin. Simplified after MILLER *et al.* (1955).

than the often used hypothetical figure of -0.17 (based on a sedmenit density of 2.50 and a basement density of 2.67). The computed gravity effects are therefore correspondingly greater.

In Fig. VI – 8 the computed gravity effects are compared with the observed Bouguer anomalies. On the northwestern part of both profiles there is a fair general agreement if one allows for the correction for the effect of topography and compensation in zones 1–18 (cf. Fig. VI – 1,) though the computed gravity effect is still somewhat too large. On the southeastern part there is no agreement.

If the isostatic corrections are taken into account it appears that the

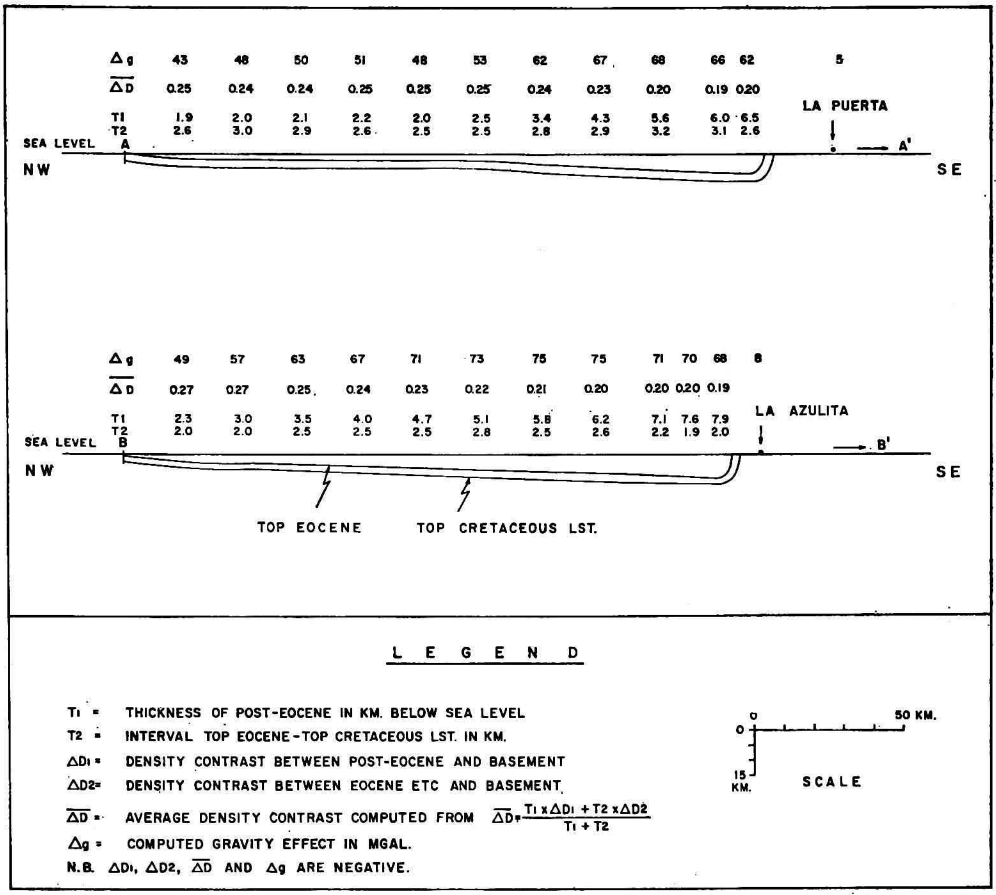


Fig. VI – 7. Computed gravity effect of light sediments in the Maracaibo Basin.

computed anomalies are, in general, too large. In the deepest part of the observed gravity minimum the computed anomalies are too small. This is true both for local ($T=30$ km, $R=0$) and regional ($T=30$, $R=232.40$ km) isostatic anomalies (cf. Fig. VIII – 3 and VIII – 4).

Acceptance of the well core density information shown in Fig. VI – 4 therefore does not yield a satisfactory explanation of the gravity field of the Maracaibo Basin as the computed gravity effects are too large. It may be added that even if the agreement between computed and observed gravity were better, the result would still be unsatisfactory from the structural point of view. For, if the agreement between the Bouguer anomalies and the computed anomalies were satisfactory, it would be necessary to conclude that the bottom of the crust in the Maracaibo Basin is unaffected by the presence of the basin. This concept of a perfectly horizontal bottom of the crust underneath a deep and comparatively young basin seems unacceptable. It would create a number of difficult questions about the evolution of basins without giving more than a formal

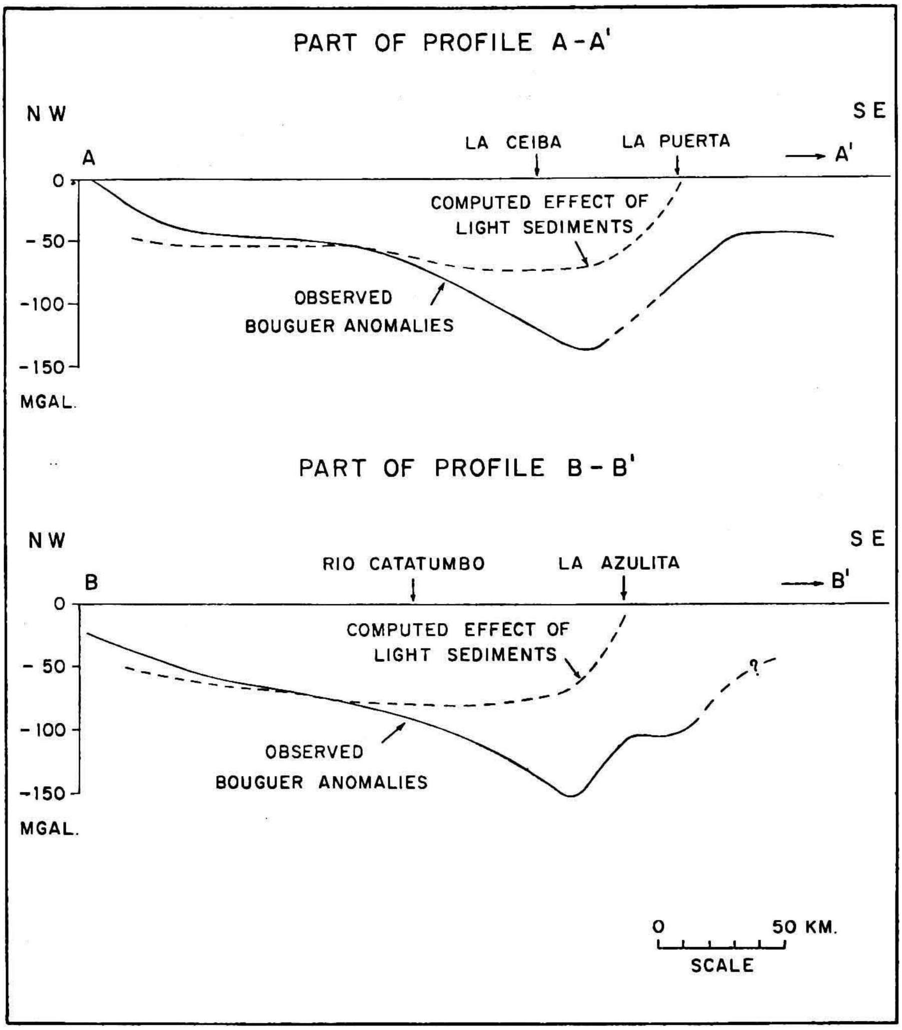


Fig. VI – 8. Comparison of computed gravity effect of light sediments in the Maracaibo Basin with observed Bouguer anomalies.

answer to the question how the negative gravity values of the Maracaibo Basin originated.

The same difficulty would present itself if the computed anomalies were able to account for the isostatic anomalies. In that case, the bottom of the crust underneath the Maracaibo Basin would be only slightly affected by the presence of the basin. Its position would bear no reasonable relation to the known depths of the basin.

For these reasons part of the density information must be considered as unreliable. Before reconsidering the evidence, however, we shall first investigate one other possible alternative or additional cause of the negative anomalies of the Maracaibo Basin, namely the presence of a downwarp of the crust, pushing lighter crustal matter into the denser substratum.

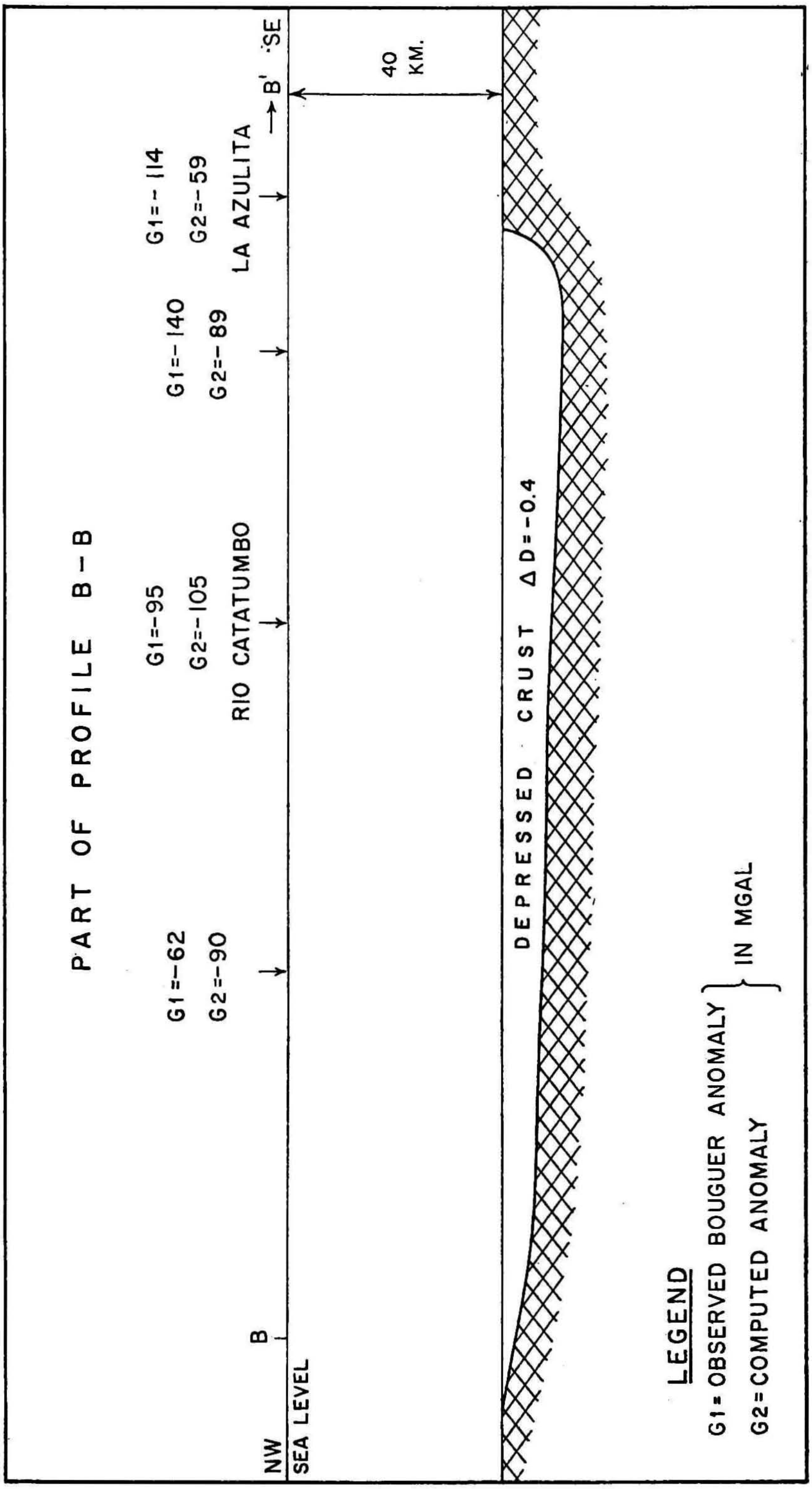


Fig. VI – 9. Computed gravity effect of a depressed crust underneath the Maracaibo Basin.

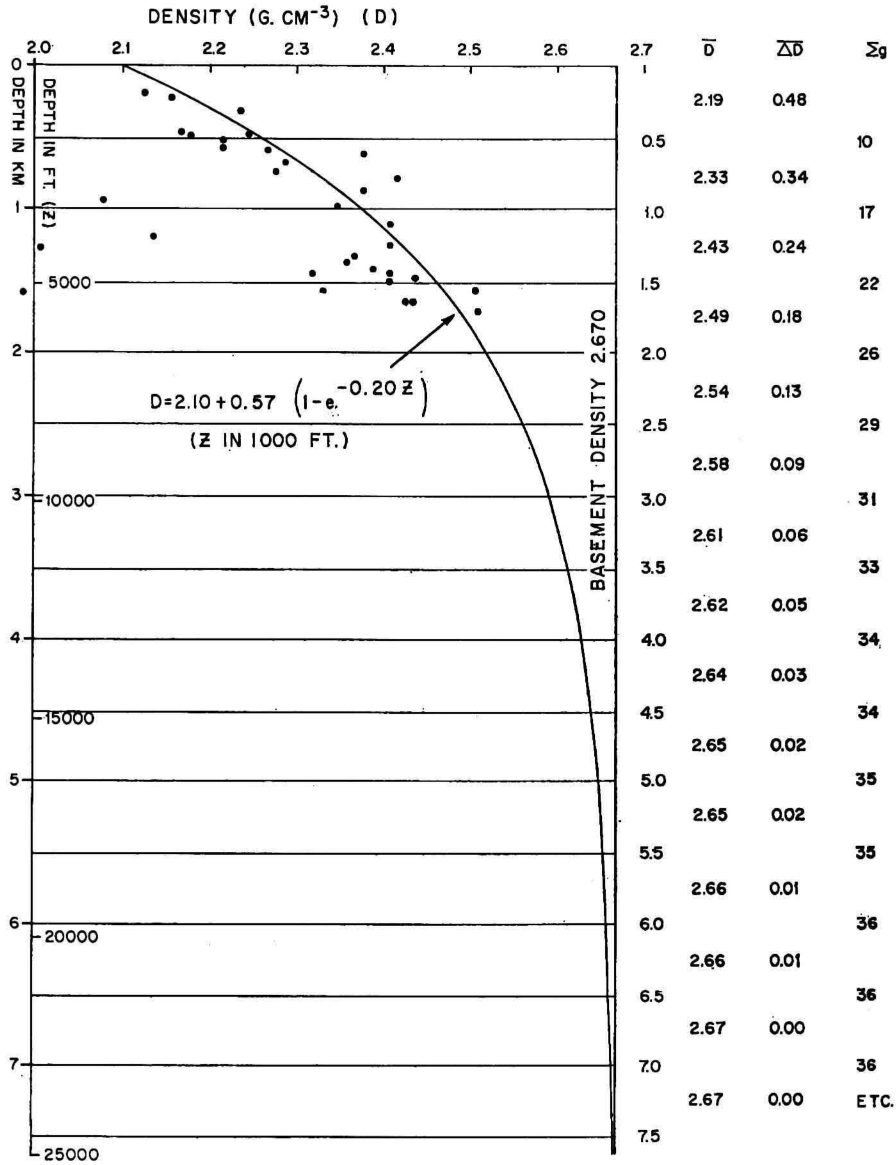
If this assumption is to be of real value one must be able to make a definite assumption about the shape of the bottom of the crust. One way of doing this is by assuming that in the Maracaibo Basin the lower surface of the crust is depressed by an amount corresponding to the depth of the (Pre-Cretaceous) basement below sea level. The latter depths are known from data published by MILLER *et al.*, (1955).

In Fig. VI – 9 the computed values on a part of profile B–B′ are shown for a crustal downwarp derived from depths to basement, assuming a density contrast of 0.4 between crust and substratum. Comparison with the observed Bouguer anomalies shows that on the greater part of the profile the computed anomalies exceed the observed ones. For a density contrast between crust and substratum exceeding 0.4 and for a crustal thickness of less than 40 km, the computed gravity effect will become still larger. As we shall see below, the computed values must be reduced quite appreciably (20 % on profile B–B′) because the assumption that the downwarp is two-dimensional is far from the truth. Nevertheless, the above discussion shows that a crustal depression or downwarp derived from depths to the top of the basement can easily account for the observed negative anomalies on the greater part of the profile.

The best explanation of the negative anomalies of the Maracaibo Basin, it seems to the present authors, is one which combines the negative gravity effects of both light sediments and a crustal downwarp which, however, is less pronounced than a depression derived from depths to basement. The solution proposed is therefore as follows.

It is assumed that the density information shown in Fig. VI – 4 is unreliable in that the measured densities are partly too low to be representative of the sampled formations. The errors are least serious for the Eocene samples. The density contrast with the basement is very small in any case at the depths where the Eocene is found. In fact, assuming that the Eocene density depth relation applies to Paleocene and Cretaceous sediments above the Cretaceous Limestone as well, the gravity effect arising from all these strata is seldom more than 10 mgal (on these assumptions Fig. VI – 7 was based). We might therefore still consider the Eocene density-depth relation of Fig. VI – 4 as correct, but only apply it to Eocene strata. However, below we shall introduce a new density-depth relation for the Post-Eocene strata. If this new relation for Post-Eocene strata were used in conjunction with the old relation for Eocene strata, the Eocene would be lighter in places than the overlying, younger, Post-Eocene. To avoid this, it is simply assumed that the Eocene and older sediments have a density 2.670, equal to that of the basement.

The error is more serious for the Post-Eocene sediments. Using data and a formula derived by J. Carr for densities found in a well in the Maracaibo Basin penetrating about 5, 500 ft of Post-Eocene, it is now assumed that the following density-depth relation holds for the Post-Eocene:



L E G E N D

D̄ = AVERAGE DENSITY OF EACH 1/2 KM.

ΔD̄ = AVERAGE DENSITY CONTRAST FOR EACH 1/2 KM.

Σg = CUMULATIVE GRAVITY EFFECT IN MGAL (NEGATIVE)

Fig. VI – 10. Density-depth relation for Post-Eocene strata (after J. Carr).

$$D = 2.10 + 0.57\ (1 - e^{-0.20Z})\ \text{g/cm}^3$$

where D is the density, and Z is the depth in thousands of feet.

If the depth (Z') is expressed in km, the formula is:

$$D = 2.10 + 0.57\ (1 - e^{-0.656Z'})\ \text{g/cm}^3$$

This relation as well as the basic data are illustrated in Fig. VI – 10 where are also shown the cumulative gravity effects to be expected from it. The maximum gravity effect due to light sediments is thereby reduced to – 36 mgal, or to about half of what had been found earlier.

It is interesting to point out in this connection that TSUBOI (1956) found that the maximum gravity effect to be expected from a nearly 10 km thick layer of sediments in the Central Valley in California, U.S.A., is at most – 30 mgal. The natural compaction of sediments (shales in particular) would therefore seem to impose a limiting value on the gravity effect to be expected from thick sedimentary series. The density contrast appears to be concentrated in the upper few kilometres of sediment (cf. Fig. VI – 10).

It is thought that this new relation (Fig. VI – 10) is much to be preferred to the previous one (Fig. VI – 4). The exponential function is also in much better agreement with work by others (ATHY, 1930; HEDBERG, 1936) than the original straight line. It means, however, that the value of core density determinations such as those shown for depths exceeding 2000 m in Fig. VI – 4 (Post-Eocene) is seriously questioned.

In order to estimate the effect of a depressed crust, a density contrast of 0.60, based on an average crustal density of 2.67 and a substratum density of 3.27 is provisionally assumed. One might equally well assume, as has been done recently by J. L. WORZEL and G. L. SHURBET (in POLDERVAART, 1955, pp. 87–100), that the average crustal density is 2.84. In either case the effective density contrast operative when a depression of the crust occurs, equals the difference of the density of the substratum (3.27) and that of the surface layers (2.67 or less). The only difference is that for the first case the density contrast due to a depression of the crust is mainly concentrated at the bottom of the crust; for the second case a relatively greater part of the contrast is situated at shallow depth. As it is known from the density study of the Venezuelan Andes that the basement density is 2.67, the present authors find it more convenient to assume an average crustal density equal to that figure. This assumption does not affect the conclusions to be reached below.

The shape of the bottom of the crust is not derived from the depths of basement below sea level, but from depths to Top Eocene (base of the Post-Eocene) in the Maracaibo Basin. This means that the Eocene and older sediments overlying the Pre-Cretaceous basement are considered as constituting part of the normal crust. Their total thickness is of the order of 3 to 3.5 km on our profiles A–A′ and B–B′. It also means that on our profiles the crust is assumed to have been more or less in floating equilibrium before the orogeny responsible for the formation of the Venezuelan Andes started.

These assumptions will be incorporated in later sections, and they will then be seen to lead to a satisfactory explanation of the observed gravity data. The following conclusions can therefore be drawn:

1) A geologically acceptable picture of the deeper structure of the Maracaibo Basin can be obtained by assuming the negative gravity values to be due to light Post-Eocene sediments combined with a crustal downwarp (i.e., the crust having been pressed into the heavy substratum).

2) The density contrast between sediments and basement is less than one might expect from density determinations on well cores.

3) Assuming the sedimentary cover of Cretaceous-Eocene sediments to be part of the normal crust, the bottom of the crust is depressed below its normal position by an amount corresponding to the depth of Top Eocene below sea level.

d. *The Barinas-Apure Basin*

Density information is not available for the Barinas-Apure Basin and therefore very little can be said about it. Nevertheless, it is of interest to subject the Barinas-Apure Basin to the same kind of investigation as the Maracaibo Basin. The sediments are divided into Post-Eocene, Eocene, and Cretaceous sediments and the linear density relations originally found for the first two groups in the Maracaibo Basin (Figs. VI – 4 and VI – 5) applied to them. In Fig. VI – 11 a section across the Barinas-Apure Basin is shown. The information on the shape of the basement and the thickness of Post-Eocene and Eocene have been obtained from a section published by YOUNG *et al.*, (1956, Fig. 14). The position of the section is shown in Fig. IV – 4 (section Barinas-A″).

The correspondence between observed and computed anomalies (the latter are indicated as "computed gravity effect I" in Fig. VI – 11) is unsatisfactory, as the computed values are too large.

If we apply the density-depth relation for Post-Eocene strata shown in Fig. VI – 10, the computed gravity effect ("computed gravity effect II" in Fig. VI – 11) is less but still not in agreement with the observed anomalies.

The gravity effect of a crustal downwarp derived from basement depths underneath the Barinas-Apure Basin must also be considered. The depression of the basement in the Barinas-Apure Basin amounts to about 4 km; for a density contrast of 0.6 this would produce gravity effects more negative than the observed anomalies. The difficulty encountered here is therefore the same as that for the Maracaibo Basin: accounting for the negative gravity values by assuming a depression of the crust corresponding to basement depths creates difficulties because the effect is too large.

The following solution, which will be incorporated in a later section, is therefore proposed:

It is assumed that the Eocene and older sediments constitute part of the normal crust. The depression of the bottom of the crust is then derived

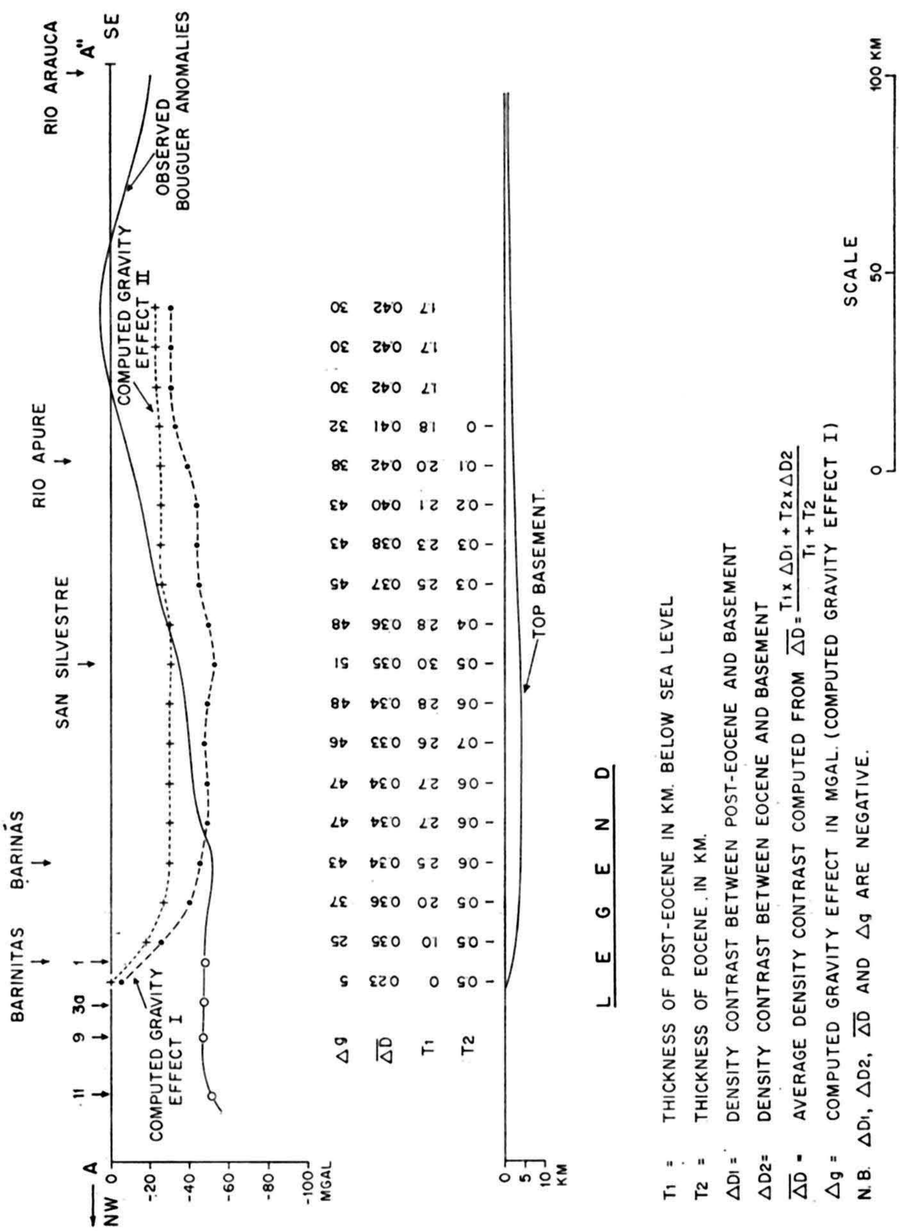


Fig. VI – 11. Computed gravity effect of light sediments in the Barinas-Apure Basin.

from depths of Base Post-Eocene below sea level. Southeast of the Rio Apure (Fig. VI – 11) Post-Eocene sediments rest directly on Cretaceous and, farther southeast, on basement. Part of the Post-Eocene or, on the extreme southeastern part, all of the Post-Eocene, may therefore have to be included in the normal crust.

The conclusions to be drawn here are as follows:

1) A geologically acceptable picture of the deeper structure of the Barinas-Apure Basin can be obtained by assuming that the larger part of the negative gravity anomalies is due to a depression of the crust.
2) The bottom of the crust is depressed below its normal position by an amount corresponding to the depth of the base of the Post-Eocene below sea level. This is not true on the southeastern part of the profile; there it must be assumed that a part or all of the Post-Eocene is part of the normal crust.

e. *The Venezuelan Andes*

The effect of light sediments in the basins adjacent to the Venezuelan Andes is only noticeable for stations outside the Andes. The effect on stations in the Andes is so small as to be negligible. However, the crustal downwarps underneath these basins exert a more pronounced influence due to their larger mass deficiency and greater depth. There is therefore reason to consider the effect of these downwarps on stations in the Andes. Having corrected for this effect one is then left with the effect of mass-irregularities underneath the Andes themselves.

The crustal thickness assumed is $T = 30$ km and the shape of the bottom of the crust is derived from depths to the base of the Post-Eocene. For profile B–B′ a downwarp of 1.5 times that on A–A″ is assumed in the Barinas-Apure Basin. The value assumed for the density contrast between crust and substratum is 0.6. The effect for stations La Puerta, Sto. Domingo, Barinitas, La Azulita, and Merida for this density contrast is 36, 26, 26, 60, and 36 mgal respectively (all values are negative).

A correction can be applied to the observed Bouguer anomalies at the above-mentioned stations in Fig. VI – 3 for the computed effect of the crustal depressions in the basins. If this is done, it is seen that the best system of isostatic compensation for some stations (La Puerta, La Azulita, and Merida) is one with a high degree of regionality ($R = 232.40$ km). However, for stations Sto. Domingo and Barinitas one now gets pronounced positive isostatic anomalies, even for systems with large values of R. Even with these corrections applied, there is therefore still no common system of isostatic compensation for the Andes stations.

Further consideration of the isostatic anomalies, particularly from the point of view of floating equilibrium, will be dealt with later.

At this stage it becomes more profitable to try and find an adequate explanation for the Bouguer anomalies. It may be pointed out, however, that the assumption of light sediments combined with a crustal downwarp being responsible for the negative Bouguer anomalies in the basins in itself means that a solution has been accepted in which isostatic equilibrium no longer exists, as the crustal downwarps represent strong deviations from equilibrium. It is also clear that underneath the Venezuelan Andes there is no light root providing approximate local isostatic compensation.

VII. DEEPER STRUCTURE OF THE VENEZUELAN ANDES AND ADJACENT BASINS

a. *Construction of cross sections*

In Fig. VII – 1 two sections of the Venezuelan Andes and adjacent basins are shown. Their position coincides with that of the gravity profiles A–A″ and B–B′ (Fig. IV – 4). The information on depths to basement (Pre-Cretaceous) and to the base of the Post-Eocene in the Maracaibo Basin has been obtained from MILLER *et al.*, (1955). The same information for the Barinas-Apure Basin has been obtained from YOUNG *et al.*, (1956) (profile A–A″) and from MILLER *et al.*, (1955) (profile B–B′, which has been extended to the southeast). The faults shown in the Venezuelan Andes are inspired by those shown on sections by KÜNDIG (1938), L. KEHRER and O. RENZ (in DUFOUR, 1955) and by K. HABICHT (in MILLER *et al.*, 1955).

The depression of the crust underneath the basins has been assumed to be equal to depths below sea level of the base of the Post-Eocene.

The position of the bottom of the crust underneath the Andes has been found by computations aimed at obtaining a reasonable fit between computed and observed gravity anomalies. For the crust a density of 2.67 and for the substratum a density of 3.27 has been assumed.

b. *Comparison of computed and observed gravity anomalies*

For both profiles computations have been made of the gravity effect to be expected from the assumed mass configurations. The computations have been carried out in two steps. The first series of computations takes into consideration the effect of light sediments and crustal downwarps only. From the differences between observed and computed anomalies the approximate size of the light mass underneath the Andes can then be determined and its approximate shape determined by trial and error. Subsequently, the computations are repeated taking into account the masses underneath the Andes as well. For the extreme south-eastern part of profile A–A″ the bottom of the crust has been assumed to be horizontal as it is not clear what position one may expect there. The exact position is unimportant as the effect of relatively small deviations from the position shown is negligible.

The observed data with which the computed anomalies are compared are the observed Bouguer anomalies, except on the northwestern part of both profiles. Here the correction for topography and compensation in zones 1–18 ($T = 30$ km, $R = 0$) is not negligibly small and has therefore been incorporated in the "Modified Bouguer Anomalies".

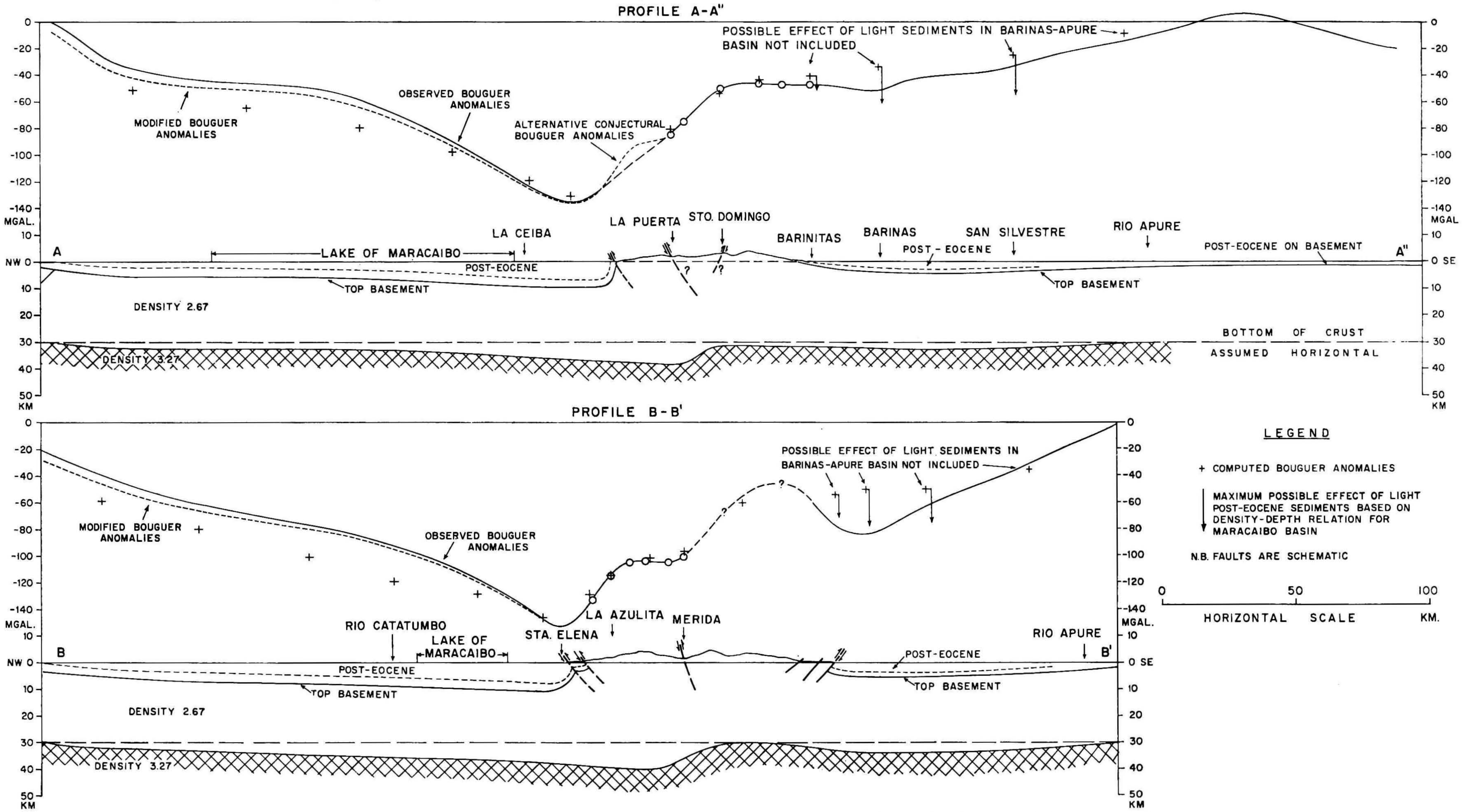


Fig. VII – 1. Deeper structure of the Venezuelan Andes with comparison of observed and computed Bouguer anomalies.

The simplest way to compute the gravity effect of the sections would be to assume the structures to be two-dimensional. This, however, is far from the truth. For the computation of the effect of the light sediments deviations from two-dimensionality need not be considered, but for the effect of the crustal downwarps these deviations are important.

The procedure chosen is as follows. First, the effect of the crustal downwarps of the Maracaibo Basin has been computed in three dimensions, following a method outlined below. Secondly, the effect has been computed, assuming perfect two-dimensionality. Comparison of these two sets of values for identical points shows that on section A–A″ the gravity effect of the Maracaibo Basin crustal downwarp computed on the assumption of two-dimensionality must be decreased by 15 % in order to yield the correct (three-dimensional) figure.

On section B–B′ this correction amounts to as much as 20 %. For the Barinas-Apure Basin there are insufficient data to compute the three-dimensional effects directly. The computations of the effect of the crustal downwarp in the Barinas-Apure Basin has therefore been carried out assuming perfect two-dimensionality. Subsequently, similar corrections as for the Maracaibo Basin (15 and 20 % for sections A–A″ and B–B′ respectively) have been applied.

The method used to compute the effect of the Maracaibo Basin crustal downwarp, duly allowing for the three-dimensional nature of the problem, is as follows. On the map of Fig. VI – 6 contours (in feet) are shown on Top Eocene in the Maracaibo Basin. It is assumed that there is a downwarp of the crust the amount of which corresponds to the depths to Top Eocene. Each contour value therefore also indicates the thickness of crustal matter below the assumed normal position of the bottom of the crust at 30 km depth. The effect at any given point on the surface can now be computed by centering on this point a template with Hayford's zones. For each zone an average thickness can then be determined, and this average thickness can be converted into an average fictitious topographic elevation by multiplying by 0.6/2.67. Entering Vening Meinesz's tables (1941) with this average fictitious topographic elevation for each zone (the tables to be used are those for $T = 30$ km and $R = 0$) one immediately obtains the desired gravity effect by summing the effects for individual zones. No appreciable inaccuracies result from the fact that the computations are only taken as far as the outside of zone O_2. This is due to the fact that the dimensions of the Maracaibo Basin are comparable to the radius of the circle representing the outer boundary of zone O_2 (cf. Fig. VI – 2).

The computation of the effect of light (Post-Eocene) sediments uses the density-depth relation shown in Fig. VI – 10. This relation has only been used for computed points in the Maracaibo Basin. In the Barinas-Apure Basin no allowance for the effect of light sediments has been made for the computed points there. However, the maximum possible effect has been indicated by the length of an arrow (Fig. VII – 1).

It is of interest to note that the unknown part of the Bouguer anomaly profile of section A–A″ between the minimum southeast of La Ceiba and La Puerta is probably not straight, as shown. On profile B–B′ on the corresponding part of the profile this part is curved and is reproduced by the computed values. This is due to a sudden jump in anomaly arising from the fact that the negative effect of the light sediments decreases very rapidly for stations situated to the southeast of the basin edge. The same therefore may be expected on profile A–A″ between La Ceiba and La Puerta.

Inspection of Fig. VII – 1 shows that there is, in general, excellent agreement between computed and observed values. This is particularly true in the Andes, and in the Barinas-Apure Basin if some allowance is made for the possible effect of light sediments.

In the Maracaibo Basin the best agreement is found on profile A–A″, on B–B′ the computed gravity values are definitely too strongly negative.

This cannot be ascribed to uncertainties in the basic data alone. There are, of course, uncertainties in the Bouguer anomalies, and in the thickness and depth information, but the discrepancies are probably due to other causes. Amongst possible causes which may contribute to the discrepancies are:

1) There may well be lateral density changes in the Post-Eocene sediments.

2) The crust-substratum density contrast may not be exactly 0.6 but somewhat less. For a density contrast of 0.43 there is a nearly perfect agreement between observed and computed anomalies.

3) The shape of the bottom of the crust is not exactly given by depths to Top Eocene. Part of the Post-Eocene may have to be incorporated in the normal crust in order to replace Eocene sediments removed by erosion.

The authors are of the opinion that the discrepancies are small compared with the general agreement between observed and computed gravity anomalies. For that reason, the interpretation given here is thought to be essentially correct.

It appears then that there exist, underneath the Maracaibo and Barinas-Apure Basins, crustal downwarps of which the amount of depression corresponds, very generally, to the depths to Top Eocene in the basins. Underneath the Andes there is an asymmetrical mass distribution, there being little or no depression underneath the southeastern range but considerable depression of the crust-substratum contact underneath the northwestern range. This solution is not essentially modified if a different crustal thickness, or a different density contrast between crust and substratum is assumed. The figures assumed for them are comparatively unimportant, the result will always be an asymmetrical mass distribution underneath the Andes.

This asymmetry points strongly to the conclusion that under compression from lateral compressive forces the crust reacted predominantly by the formation of thrust faults so that the southeastern part was thrust over the northwestern part. Along the southeastern edge of the Andes one might, however, expect faults overthrust towards the southeast.

It is quite conceivable that some major faults go right through the crust. Judging from the gravity picture such a major thrust fault is probably situated along the northwestern edge of the Venezuelan Andes. It is thought to disappear near Cucuta towards the southwest and west of Valera towards the northeast (Fig. IV – 4). Another important fault might well run along the Rio Chama and Rio Motatan valleys which divide the Venezuelan Andes into two parallel ranges.

VIII. DEFORMATION OF THE EARTH'S CRUST IN THE VENEZUELAN ANDES

a. *Types of mechanical deformation of the earth's crust.*

The gravity data of the western part of Venezuela have been used to yield a picture of the deeper structure of the Venezuelan Andes and adjacent basins. The question now arises to what extent it is possible to account for the configuration derived by assuming a simple type of mechanical failure having occurred. Elastic buckling, plastic buckling, and shear fracture will be considered here for that purpose.

In his classical studies of the gravity field of Indonesia (cf. VENING MEINESZ, 1948, 1954) VENING MEINESZ originally (first in 1930) put forward the hypothesis that the earth's crust had elastically buckled down along a relatively narrow strip under compressive stresses acting horizontally in the earth's crust. He was thus able to account for the gravity field of the Indonesian archipelago, the principal feature of which is a band of strongly negative isostatic anomalies.

The concept of elastic buckling of the earth's crust due to lateral compression has, however, met with a number of objections. The main objection is that the buckling limit of the compressive stress for a rigid crust of reasonable thickness is far too high to assume that the crust can react elastically up to that limit. A second objection is that the finite strength of the substratum underlying the crust would prevent the development of the required initial deviation from the equilibrium position. A third objection is that the assumption of elastic buckling makes it difficult to account for the shape of the belts of deformation on the map (VENING MEINESZ, 1954, 1955).

For these reasons the concept of elastic buckling has been replaced by that of plastic buckling. Plastic buckling of the earth's crust is a concept originally introduced (in 1935) by P. P. BIJLAARD. Under lateral compressive stress the crust is thought to yield plastically in a narrow strip when the yield stress has been reached; the strip of plastic deformation makes an angle of 55° with the direction of the compressive stress. The initial thickening in the belt of plastic deformation will tend to be symmetrical with respect to the adjacent parts of the crust, but as this will cause an excess load on the crust, the symmetrical thickening cannot develop because the crust in the deformed strip begins to bend down. Continued compression will then accentuate the asymmetry and a plastic buckle will develop. Cessation of compression will enable isostatic equilibrium to be restored and a mountain chain will finally emerge. The concept of plastic buckling has a firm theoretical and experimental foundation; details and references may be found in a summarizing paper by BIJLAARD (1951).

Plastic buckling of the earth's crust has been accepted by VENING MEINESZ as a better hypothesis than elastic buckling. His most recent quantitative treatment (VENING MEINESZ, 1955) gives a most attractive account of the development of geosynclines and the origin of mountain ranges. He is also able to demonstrate the excellent agreement between the predicted and the observed gravity field in the Indonesian archipelago.

Shear fracture is compared with buckling. a very simple type of crustal deformation. When the crust is under compressive stress, it is a legitimate assumption that the directions of the maximum and intermediate principal stresses are both practically horizontal and that the direction of the minimum principal stress is vertical (ANDERSON, 1951). In that case, fractures may develop along planes which are parallel to the direction of the intermediate principal stress and which form an angle $\alpha = \pm(45° - \varphi/2)$ with the horizontal. In this formula φ is the angle of internal friction, for which a value of about 30° may be assumed (HUBBERT, 1951; HAFNER, 1951).

The planes of potential shear fracture may therefore be expected to form an angle of about 30° with the earth's surface. Their surface traces are straight lines.

This type of deformation has been advocated as the main factor in mountain building by GUNN (1947, 1949; the papers referred to also contain references to his earlier work). The same type of deformation plays a role in the orogenic theory of J. T. WILSON (WILSON, 1950; from SCHEIDEGGER, 1953), and in that of RICH (1951). Crustal deformation by shear fracture has also been clearly recognized by VENING MEINESZ (1948, pp. 37, 72–74).

b. *Type of crustal deformation in the Venezuelan Andes.*

Elastic buckling having been ruled out, the only simple types of mechanical failure of the crust which might provide an explanation are plastic buckling and shear fracture. The essential asymmetry of the deeper structure of the Venezuelan Andes points at first sight to the fracture hypothesis. However, even though a plastic buckle which is symmetrical relative to a vertical plane through the axis of the mountain range cannot be present, some plastic deformation must nevertheless have occurred. The reason for this statement is that apparently (cf. Fig. VII – 1) there has been some thickening of the crust even in the overthrusting part of the crust. Plastic deformation can hence not be ruled out altogether and the inferred structure is therefore intermediate between an asymmetrical plastic buckle and a pure shear fracture [1]).

[1]) In an experimental study of crustal deformation under horizontal compression KUENEN (1936) obtained an example of shear fracture together with crustal buckling

At some depth below the earth's surface plastic deformation is also, of course, a more probable process than pure shear fracture. When hereafter shear fracture is spoken of as being the controlling factor in the origin of the Venezuelan Andes, it does not imply that there is not at least some plastic deformation.

It will be noted that plastic buckling and shear fracture have in common that both ascribe the deformation of the earth's crust to horizontal compression.

In essence, the Venezuelan Andes are therefore thought to owe their origin to the development of a plane of fracture (or zone of thrust faults) sloping at about 30° with the horizontal and forming straight fault traces along the earth's surface, along which the southeastern part of the crust was thrust over the northwestern part. This main fault or fault zone is thought to be situated along the northwestern edge of the Andes. Geological observations establish that this is essentially true, but that there is not one clear-cut thrust fault (such as that shown in Fig. VIII – 1), but that there exists a complicated series of thrust faults along which the Andes are thrust over the Maracaibo Basin.

The overthrust along the northwestern edge having started, it is an acceptable assumption that overthrusting of the Andes towards the southeast over the adjoining crust began to develop at a somewhat later stage. This overthrusting along the southeastern edge is not known so well. Locally it is probably of considerable magnitude, but on the whole it is probably much less pronounced than that along the northwestern edge.

c. *Quantitative aspects of the shear fracture hypothesis*

When the crust is subjected to lateral compression, theory establishes that there are planes of maximum shear stress which form an angle of 45° with the plane (assumed to be horizontal) containing the directions of the maximum and the intermediate principal stresses, and which are parallel to the direction of the intermediate principal stress. Because of the internal friction of the medium, shear fracture does not take place along these planes, but along planes which, though parallel to the direction of the intermediate principal stress, form an angle of less than 45° with the horizontal. As was stated earlier, there is good reason to assume that this angle is considerably less than 45°, namely about 30°. It is therefore of interest to note that an angle of 30° to 40° is in good agreement with the deeper configuration shown in Fig. VII – 1. If it is assumed that the major overthrust is situated along the northwestern edge of the Andes and dips away underneath the mountain forming an angle of between 30° and 40° with the horizontal, it appears from the profiles in Fig. VII – 1. that the fault plane reaches the substratum in such a place that the

(his Fig. 12). This illustrates how the crust may react in an extreme case of excessive compression and how the two types of deformation may combine in a single orogenic belt.

asymmetrically placed light root can be interpreted as a logical part of the underthrusting part of the crust.

Another point of interest is that the shear fracture hypothesis requires that the mountain front, at least on the northwestern side, should be straight. This is indeed the case, as any topographical map will show.

Other, more strictly quantitative considerations can be based on the work of GUNN (1947). GUNN assumes that the earth has a strong elastic crust which is hydrostatically supported by an underlying denser substratum. The type of deformation under systematic compression he accepts as most adequate is overthrusting and underthrusting at shear faults in the crust. The theoretical case he considers is two-dimensional, the vertical cross-section being oriented parallel to the direction of the horizontal compressive stress and hence at right angles to the shear fracture. The thrust fault is assumed to coincide with a plane of maximum shear stress (forming an angle of 45° with the horizontal). This assumption is probably somewhat less acceptable than the angle of 30° advocated here. The difference is, however, not of essential significance and does not affect Gunn's reasoning.

If a shear fracture is produced, continuing horizontal compression will produce over – and underthrusting, lifting and depressing the fractured ends of the crust. Ever increasing restoring stresses are produced which must ultimately establish a state of equilibrium.

Applying well-established laws of loaded elastically supported beams, GUNN (1947) shows that

$$y = \frac{2\,Fv\,q\,e^{-qx}\cos qx}{(do-d)\,g} \qquad \text{(Eq. 1)}$$

where

y = the upward or downward deformation of the neutral axis of the equivalent beam; practically, it is the same as the uplift or depression of the surface relative to the original level of the surface of the crust (here assumed to be sea level).

Fv = the vertical force acting on the broken end of the section
= $ST \cos \varphi$ sine φ

S = the horizontal compressive stress

T = the thickness of the crust

φ = the angle which the shear plane makes with the direction of the compressive stress S

q = $\sqrt[4]{\frac{3\,(do-d)\,g}{ET^3}}$

do = the density of the substratum

d = the density of sediments or water covering the depressed part of the crust if such is the case

g = the acceleration of gravity

E = the modulus of elasticity

e = the base of the natural system of logarithms
= 2.71828 . . .

x = the horizontal distance along the section from the point where the shear fault intersects the earth's surface.

The structure is assumed to be two-dimensional, that is, of infinite extent in the direction at right angles to the section. The above quantities apply to a section of unit width.

This formula describes the shape of the overthrusting part of the crust (where $d=0$) if it is assumed that no erosion occurs. It also describes the shape of the underthrusting part of the crust if it is assumed that the depressed part of the crust is not covered by water or sediments, and hence $d=0$. In this case the overthrusting and the underthrusting crustal tracts are deformed by equal amounts but in opposite directions.

If it is assumed that as soon as the depression begins to form, it will be kept filled with water, $d=1$ for the underthrusting part of the crust. In that case, again assuming that no erosion or sedimentation occurs, the deviations of the crust from the original position in the overthrusting and underthrusting parts are of opposite directions and similar, but no longer equal; the underthrusting part is relatively more depressed. The situation is then as schematically shown in Fig. VIII - 1 (Stage II).

Gunn subsequently computes the fibre stresses in the crust induced by the shear fracture and following over-and underthrusting. He shows that the maximum fibre stress occurs at the value of x' defined by

$$\tan bx' = \frac{b}{a} \qquad \text{(Eq. 2)}$$

where:

x' is the same as x above except that the origin is taken vertically above the centre of the shear plane,

$$a = \pm \sqrt{q^2 - \frac{3S}{ET^2}}$$

$$b = \pm \sqrt{q^2 + \frac{3S}{ET^2}}$$

and q, S, E, and T are as defined above.

At the value of x' defined by Eq. 2 secondary failure may be expected as the crust is bent more and more by the applied horizontal compressive stress. From the above it follows that secondary failure due to the maximum fibre stress may occur in the overthrusting block at a distance x_0 from the surface trace of the fracture, so that

$$x_0 = \frac{T}{2} \cot \varphi + \frac{1}{b} \tan^{-1} \frac{b}{a} \qquad \text{(Eq. 3)}$$

From Eq. 1 it follows that y becomes zero for $x=\pi/2q$, so that the total width (X) of the overthrusting and underthrusting belt is given by

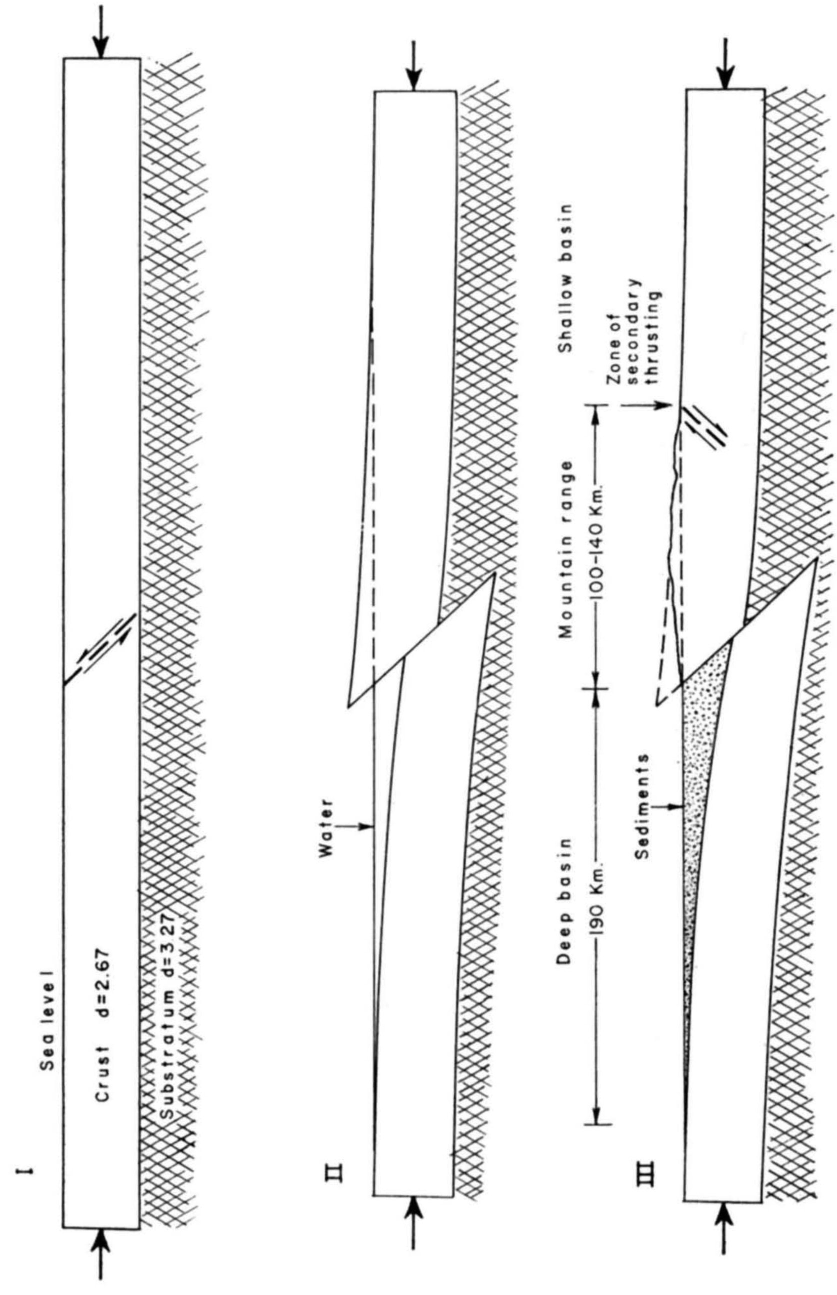


Fig. VIII – 1. The formation of a mountain range and basins according to the shear fracture hypothesis.

$$X = \frac{\pi}{q} \qquad \text{(Eq. 4)}$$

From studies of observational data Gunn has derived an average value of

$$q \simeq 8.4 \times 10^{-8} \text{ cm}^{-1}.$$

This value of q may imply that

$$E \simeq 1.1 \times 10^{12} \text{ dynes/cm}^2$$

and

$$T \simeq 50 \times 10^5 \text{ cm},$$

but other combinations are possible.

For S a figure which is a small number times 10^9 dynes/cm² is taken. By numerical substitution it then follows that a and b are nearly equal and approximate the value of q.

GUNN takes for φ the value $\pi/4$ or 45° and for do the value 3.1 g/cm³. Here we shall use

$$\varphi = 30° = \pi/6 \text{ rad.}$$

The above theoretical considerations may be applied to the Venezuelan Andes and adjacent basins as follows.

From Eq. 4 it follows that the total width of the deformed belt is

$$X = 375 \text{ km}$$

This figure is in good agreement with the cross sections in Fig. VII – 1.

Similarly, the width of the Maracaibo Basin should be of the order of

$$\tfrac{1}{2} X = 190 \text{ km.}$$

This agrees very closely with the actual basin width depicted in Fig. VII – 1.

Important secondary phenomena may be expected where, according to Eq. 3, the fibre stress is a maximum in the overthrusting block. In the Venezuelan Andes the fibre stress is at its greatest at a distance of

$$x_0 = 43 + 93 = 136 \text{ km from the fault trace.}$$

This is only in fair agreement with the observed value of 100 km. The discrepancy can be reduced by half by assuming $\varphi = 45°$ though this is an unattractive assumption. A smaller value than 50 km for T also helps to reduce the discrepancy. It is therefore reasonable to assume that the overthrusts at the southeastern edge of the Andes are formed as a secondary feature in a zone where the fibre stress reaches a maximum. This is in agreement with the fact that in the overthrusting sector the uppermost layers are in compression due both to the deformation and to the superposed horizontal compressive stress. In the upper part of the underthrusting sector, however, the deformational stress is reversed; a corresponding feature therefore cannot be expected in the underthrusting part of the crust.

In Fig. VIII – 1 the shear fracture hypothesis has been represented diagrammatically and strongly exaggerated. Stage II is, of course, never realized. As soon as deformation starts, erosion attacks the overthrusting sector and deposition of sediments starts in the underthrusting sector. Some time after the main shear fracture is formed, secondary thrusting begins in the zone of maximum fibre stress. The secondary thrusting forms a shallow basin. The angle of the shear fault in the figure has been taken as 45°; the effect of erosion and deposition is illustrated by Stage III of the figure.

It is thought that Gunn's hypothesis of shear fracture provides a fairly adequate model with which to account for the main features of the observational data discussed in this section and represented in Fig. VII – 1. The principal additional refinement which the model requires in order to be in complete harmony with the inferred structure in nature is that it appears necessary (as discussed above) to assume some plastic deformation in the mountain range.

d. *Final isostatic considerations*

One other aspect of the crustal deformation in the Venezuelan Andes is the question to which extent the crust is in isostatic equilibrium. It is clear that the overthrusting part of the crust is above its equilibrium position, and the underthrusting part below it (Fig. VIII – 1). Hence there is no local isostatic compensation. Yet it is true that at equal distances from the surface trace of the shear fracture the mass excess in a vertical prism of a given cross-sectional area in the overthrusting crust equals the mass deficiency in a similar vertical prism of the underthrusting crust. The downward and upward forces on the crust must therefore cancel each other. The light mass compensating the mountain range is displaced laterally and situated underneath the basin.

As the time required for the crustal deformation responsible for the formation of geosynclines and mountains is measured in millions or tens of millions of years, and the time required to even out deviations from equilibrium such as the depression of Fennoscandia due to the load of the Pleistocene ice cap is measured in only tens of thousands of years, the conclusion seems to be justified that in fact the cancellation of vertical forces continues right through the entire process of deformation.

In the preceding section a total width of the deformed belt of nearly 400 km was found. Assuming exact two-dimensionality, the integrated upward and downward forces along a cross section of the entire deformed belt must, with a view to the above, add up to zero. As the upward and downward forces are proportional to the mass deficiencies and mass excesses respectively, the same must, to a first approximation, be true of the isostatic anomalies (Gunn, 1949).

In order to check this point, it is not sufficient to restrict oneself to the isostatic anomalies which have been computed thus far. The ordinary isostatic corrections correct for the possible compensation of the visible topography. This implies that the sedimentary fill of basins is tacitly assumed to have a density of 2.67. This is certainly not the case for the Maracaibo Basin where effects of as much as – 36 mgal may arise from the difference between the real density and the standard density of 2.67.

Systematic corrections for such effects were first applied by Evans and Crompton (1946). The procedure consists of first correcting the ordinary isostatic anomalies for the difference between the actual and assumed sediment densities in a basin, and subsequently allowing for the isostatic compensation needed to take account of the density deficiency of the sediments.

The sign of these corrections is found as follows. The measured gravity values contain the influence of the light sedimentary fill of the basin. In order to reduce this fill to the standard density of 2.67, a positive correction, which cancels the negative effect of the sediments, must be applied to the observed values, that is, to the ordinary isostatic anomalies. In the deeper parts of the Maracaibo Basin this is a correction of + 36 mgal. It will be referred to as the "geological correction". The correction which cancels the isostatic compensation of the mass deficiency has the opposite sign. It will be referred to as the "geological isostatic correction". In all practical instances the absolute value of the geological correction exceeds that of the geological isostatic correction for stations near the centre of the basin. Near the centre of the basin the combined correction is therefore positive and makes the ordinary isostatic anomalies less negative.

The computation of the geological correction presents no difficulties as the conventional formula for the gravity effect of a slab of infinite horizontal extent can be used. Near the edges of the basin a suitable correction can easily be made.

The computation of the geological isostatic correction requires more elaborate methods. Starting from the known thicknesses of the Post-Eocene sediments in the Maracaibo Basin (Fig. VI – 6) and the density-depth relation for these sediments (Fig. VI – 10) the Post-Eocene thickness at any point can be converted into the corresponding mass deficiency. This mass deficiency can be expressed as a fictitious negative topographical height combined with a density contrast of 2.67. When this has been done for a large enough number of points a contour map of the fictitious negative topography can be prepared.

For example, assume that at a given point the thickness of the Post-Eocene (according to Fig. VI – 6) is 15,000 ft or 4,570 m. The mass deficiency is computed from Fig. VI – 10; per cm^2 the mass deficiency is 8.01×10^4 gm. This corresponds to a fictitious negative topographical height of 0.300 km for a density contrast of 2.67.

The geological isostatic correction can subsequently be computed at any desired point by centering on it a template with the Hayford zones A–O_2. For each zone an average fictitious negative topographical height can then be found. Entering the tables of VENING MEINESZ (1941) with the the average zone heights (using the tables only for the positive values of h) the desired correction per zone can then be obtained (without changing the sign of the value read in the table) for the required system of isostatic compensation. The total effect is found by summation of the zone effects.

It may be remarked that no appreciable inaccuracies result from taking the computations only as far as the outside of zone O_2. This is due to the fact that the dimensions of the Maracaibo Basin are comparable to the radius of the outer boundary circle of zone O_2 (cf. Fig. VI – 2).

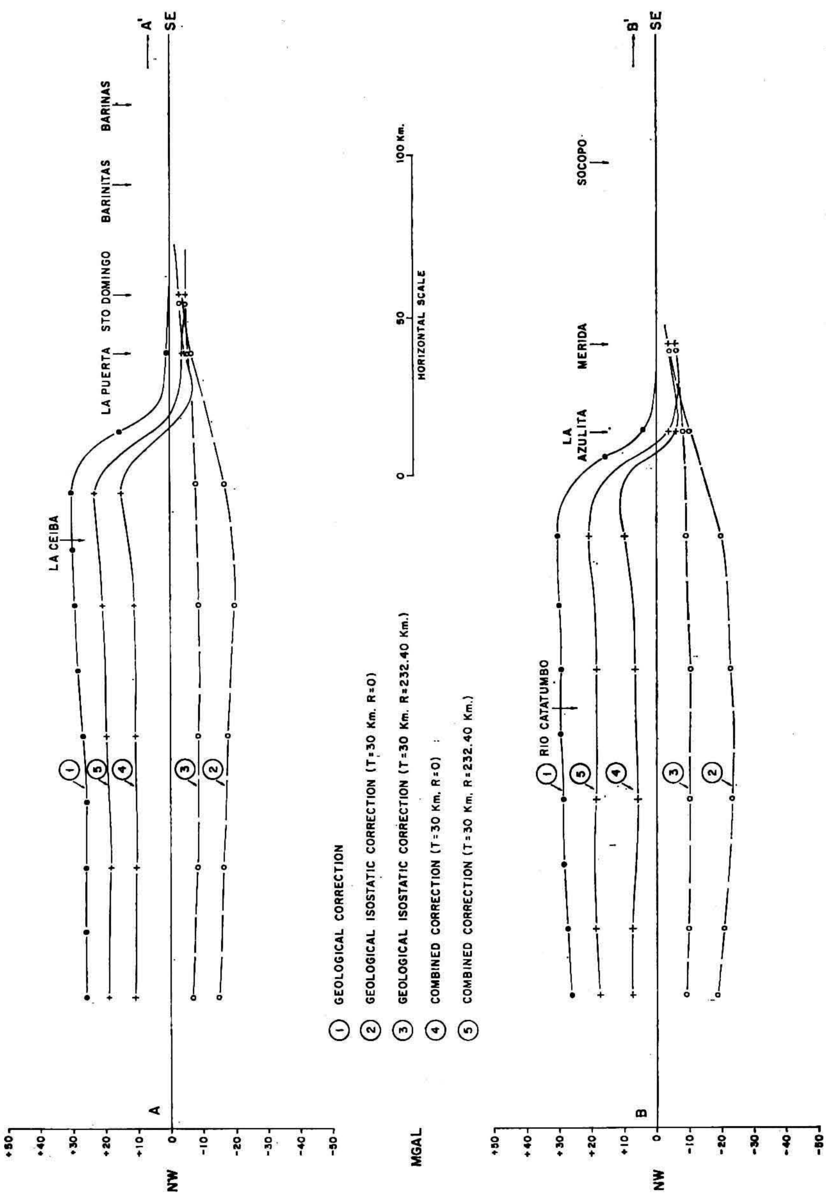


Fig. VIII – 2. Geological and geological isostatic corrections in the Maracaibo Basin.

In Fig. VIII – 2 the geological corrections, the geological isostatic corrections (for $T = 30$ km, $R = 0$ and for $T = 30$ km, $R = 232.40$ km), and the combined corrections are shown for profiles A–A′ and B–B′ in the Maracaibo Basin and the Venezuelan Andes.

On each profile the geological isostatic corrections are, in absolute value, smaller than the geological corrections. The geological isostatic correction for $R = 232.40$ km is smaller than the one for $R = 0$, but varies less abruptly. The combined correction for local compensation is hence considerably smaller than that for regional compensation; the former is of the order of $+10$ mgal, the latter of $+20$ mgal. For the Andes stations the combined corrections are of the order of -5 mgal or less.

These results will now be considered in conjunction with the ordinary isostatic anomalies. In Fig. VIII – 3 the observed Bouguer anomalies and the computed isostatic corrections for a number of points along the profiles A – A″ and B – B′ are shown, as well as a schematic curve giving the approximate value of the isostatic corrections between the computed points. The latter curve is based on computations by Mr. L. L. Mattens and on Table V – 2. The choice of $T = 30$ km is a matter of convenience, for other values of T (cf. Fig. VI – 3) similar results are found.

The (ordinary) local isostatic anomalies ($T = 30$ km, $R = 0$) are positive in the southeastern part of the Andes (up to $+70$ mgal), negative in the basins, particularly in the Maracaibo Basin (down to -100 mgal). The contrast is less for the (ordinary) regional isostatic anomalies ($T = 30$ km, $R = 232.40$ km). In the Andes they are weakly positive, in the Maracaibo Basin they nearly reach -100 mgal.

Fig. VIII – 4 shows for profiles A–A″ and B–B′ the isostatic anomalies fully corrected for the light sedimentary fill of the Maracaibo Basin and its accompanying isostatic compensation, i.e., incorporating the geological and geological isostatic corrections. These anomaly curves are derived by combining the ordinary isostatic anomalies of Fig. VIII – 3 with the combined corrections of Fig. VIII – 2. One curve is for $T = 30$ km, $R = 0$; the other for $T = 30$ km, $R = 232.40$ km. No corrections have been computed or incorporated for the Barinas-Apure Basin. The effect to be expected is probably small, smaller than in the Maracaibo Basin in any case.

The curves represent the deviations from floating equilibrium. Qualitatively they show the complementary anomaly values required by the shear fracture theory, advocated here as the best explanation of the gravity field of the Venezuelan Andes. Quantitatively, the required equivalence of the positive and negative anomalies is not clear at once as on both profiles both for the local and regional anomaly curves the negative values predominate.

This may in part be due to the fact that the average isostatic anomaly over the area need not be zero. The deviation may be quite appreciable; for Europe the average is $+13$ mgal (de Bruyn, 1955), for Indonesia about $+30$ mgal (Vening Meinesz, 1948, p. 64). In western Venezuela a reference level of about -20 mgal would meet the requirements.

Also, it should be kept in mind that exact equivalence is only required when the gravity field is strictly two-dimensional. This is certainly not so for the gravity field discussed here. A much larger area should therefore be considered to settle the point with a fair degree of exactness. This will have to wait until more data are available.

The outcome of the above investigation is thought to be satisfactory, in that the fully corrected isostatic anomalies show the complementary

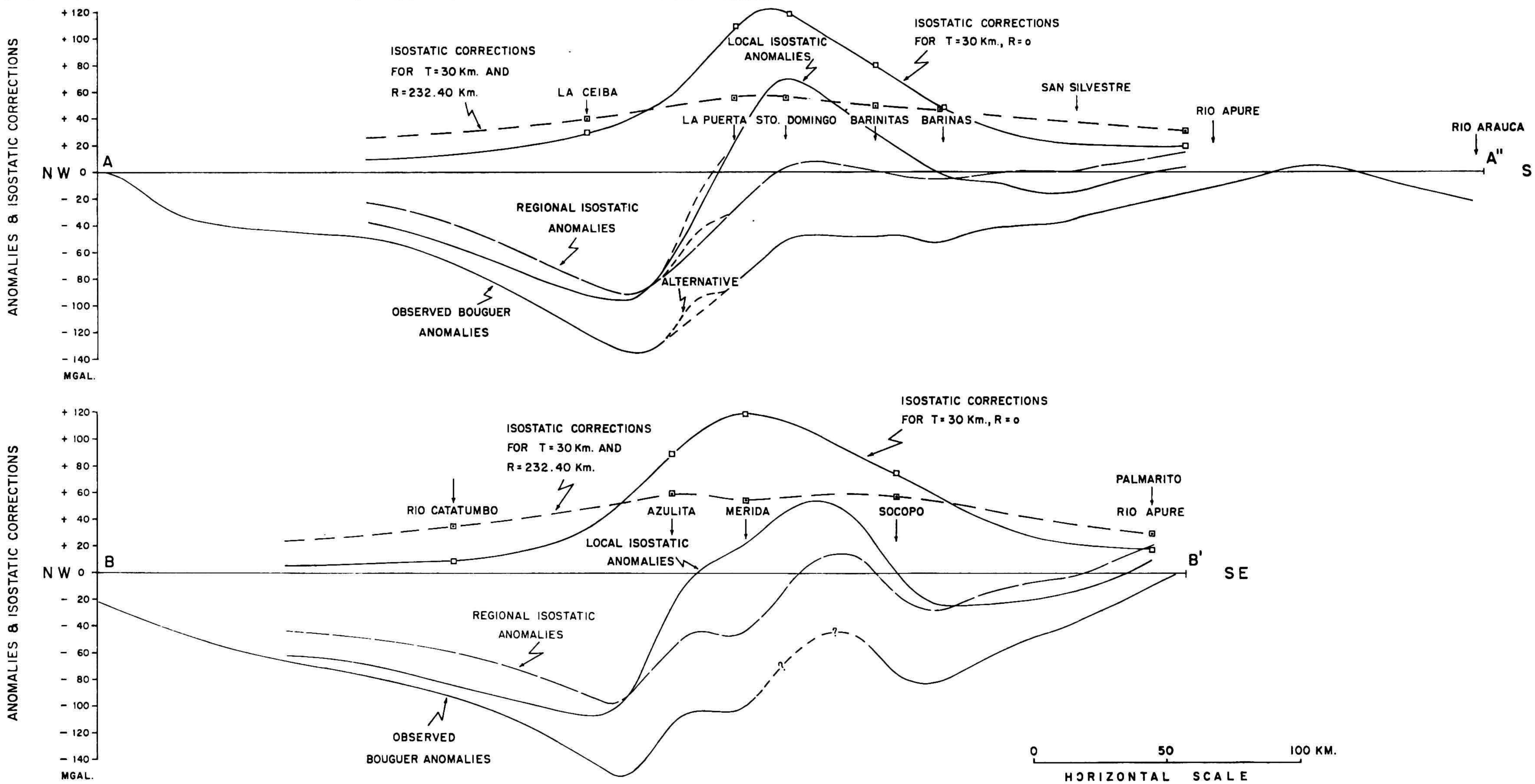


Fig. VIII – 3. Isostatic anomalies of the Venezuelan Andes and adjacent basins.

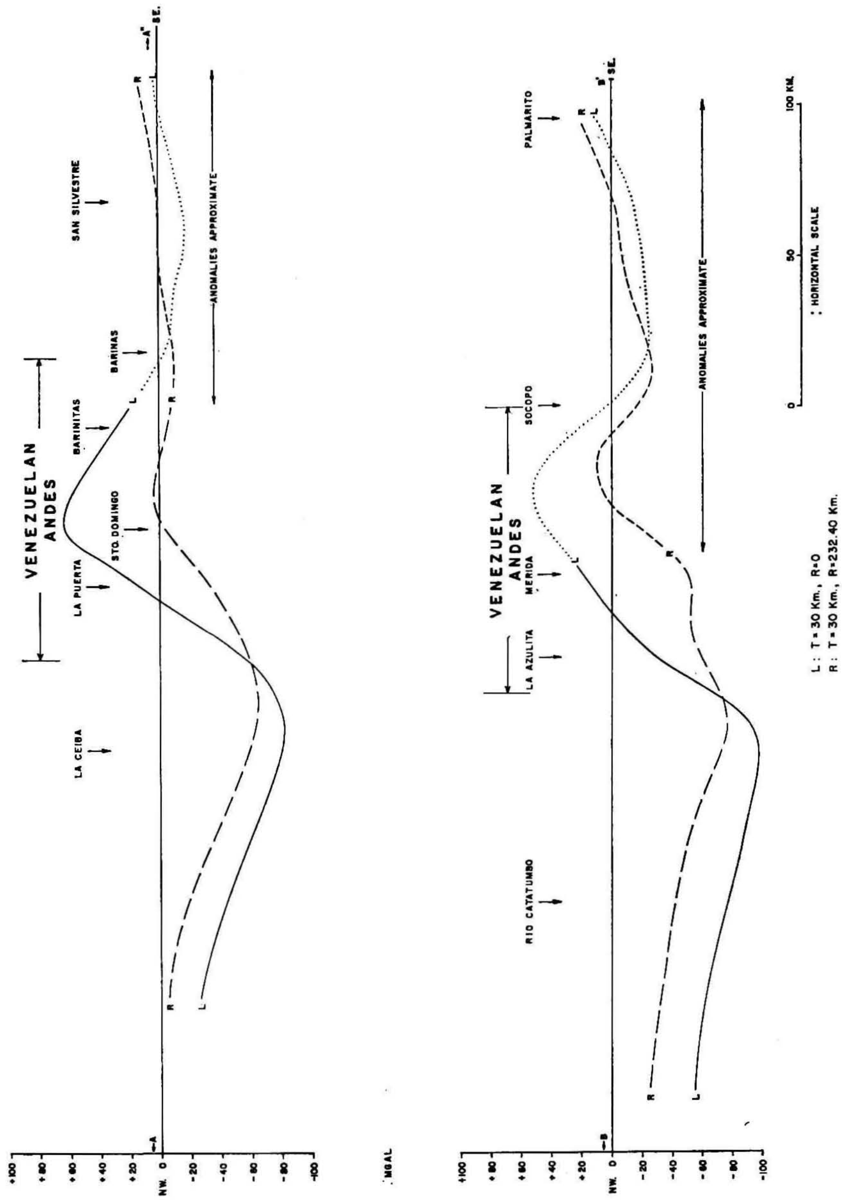


Fig. VIII – 4. Isostatic anomalies incorporating the geological and geological isostatic corrections for the Maracaibo Basin.

positive and negative values required by the shear fracture hypothesis. To a first approximation, the topography of the Venezuelan Andes is therefore compensated by a light "root" which is not situated underneath the mountain range itself but underneath its north-western edge and the adjoining Maracaibo Basin.

Present-day vertical movements of the Venezuelan Andes and the Maracaibo and Barinas-Apure Basins are a subject on which the present theoretical considerations throw no light. If the compressive orogenic stresses still act in sufficient intensity to bring about further sliding along the major fault or fault zones, the Andes will rise and the basins subside. If not, the present situation will be maintained except for the continuing effects of erosion and sedimentation. If the compressive stresses cease altogether and it is accepted as possible that the movements along the faults can be reversed, the mountain range will sink and the basins will rise. The available factual evidence, as was discussed before, is not conclusive and therefore the question of the present-day movements must be left undecided. One thing, nevertheless, appears to be a sound inference; if there are any movements, they must be of opposite directions for mountains and basins.

IX. CRUSTAL SHORTENING, WRENCH FAULTS, AND DIRECTION OF OROGENIC STRESS

a. *Crustal shortening.*

The gravity data can be used to yield information on how much extra light crustal material there is underneath the Venezuelan Andes. It is also possible to estimate roughly the amount of sediments derived from the Andes, and from the known topography one knows how much mass there is above sea level. Hence it is possible to compute the amount of crustal shortening which has occurred in the Andes.

On profile A–A″ a normal crust of 30 km thickness has been assumed. This crust has been pressed down underneath the basins, but in addition to the light masses thus created, there is extra light matter underneath the Andes. From Fig. VII – 1 its cross-sectional area is estimated at 250 km^2 (density 2.67). The topography above sea level here is estimated at 130 km^2 (density 2.67). The amount of Post-Eocene sediments also has to be taken into account, but it cannot be assumed that it all came from the Andes and that the material has only moved along the profile. For the Maracaibo Basin the total cross-sectional area is 650 km^2, for the Barinas-Apure Basin 160 km^2. For both an average density of 2.5 is taken; for density 2.67 the sum becomes 750 km^2. For the calculation it is assumed that only half of it was derived from the Andes (375 km^2). If only the "root" of the Andes and the topography above sea level are taken, one gets 380 km^2. For a normal crustal thickness of 30 km this amounts to a shortening of 13 km. Adding the sediments as well, one gets about 12 km more, adding up to 25 km.

On profile B–B′ the cross-sectional areas for the light root, the topography above sea level, and half of the Post-Eocene sediments of the Maracaibo and Barinas-Apure Basins are 375, 190, 450 and 120 km^2 respectively. For a normal crustal thickness of 30 km this amounts to a crustal shortening of about 38 km.

If it is assumed that the density contrast between crust and substratum is not 0.6 but 0.3, the estimates increase by about 10 km.

Calculations of this kind are inaccurate because of the uncertainties in the basic assumptions. Nevertheless, there is reason from the above to state that crustal shortening in the Venezuelan Andes is at most of the order of 50 km.

For a geological estimate of the shortening a section published by Dufour (1955, Fig. 7; section by L. Kehrer and O. Renz) can be used. This section lies approximately along gravity profile A–A″. On this section, the base of the Cretaceous can be followed from Lake Maracaibo to Barinas across the Andes, except for a distance of about 18 km in the highest part of the mountains. The reconstructed total length of the base of the Cretaceous is about 182 km, allowing for the gap of 18 km by adding this amount. As the present distance is 162 km, the shortening is about 20 km. This is, of course, a very rough estimate, but it shows that there is observable shortening.

Agreement with the figure derived from the gravity data (25 to 35 km on profile A–A″) is not to be expected. A part of the shortening must be taken up by movements along the thrust faults, so that a part of the length of the measured horizon is situated in the underthrusting crustal block underneath the shear fault. The gravity estimate should hence exceed the geological estimate as in fact it does.

A comparison of the figure of 40–50 km shortening arrived at for the Venezuelan Andes with the corresponding figure for the Swiss Alps obtained by the same reasoning is of interest. Using data for a profile across the Alps given by HOSPERS (1957), namely 1400 km^2 (density 2.67) for the root, 284 km^2 (density 2.67) for the topography above sea level, and 350 km^2 (density 2.67) for the sediments, one finds for a normal crustal thickness of 30 km, a crustal shortening of about 70 km. If it is assumed that the original topography is much larger than 284 + 350 km^2, namely about 600 km^2 more, the crustal shortening in the Swiss Alps becomes nearly 90 km. Geological estimates of the shortening in the Swiss Alps are still somewhat larger (DE SITTER, 1956 b).

These considerations would seem to point to a larger crustal shortening in the Alps than in the Venezuelan Andes. The crustal shortening in the Alps would appear to be at least one-and-a-half time to twice that in the Venezuelan Andes.

Finally, it must be added that the figures given for the Alps are underestimates if it is assumed that melting and spreading of the root can take place. VENING MEINESZ (in HEISKANEN and VENING MEINESZ, 1958, pp. 343–345) has demonstrated that this process has, in all probability, taken place in the Alps. A significant part of the root may have been removed by this process.

b. *Direction of orogenic stress.*

The direction of the orogenic stresses which may have been responsible for the formation of the Venezuelan Andes will now be considered. It should be stated at once that this discussion must be unsatisfactory as the time factor is left out of consideration. This means that orogeny everywhere in the area is considered as of the same age, which rules out the possibility of stresses changing direction with time. The following remarks may nevertheless be of interest.

The shear fracture of the Venezuelan Andes must be thought of as having developed at right angles (on the map) to the maximum principal stress, the compression. If it is thought that all mountains ranges of Colombia and Venezuela have originated in such a way that their axes

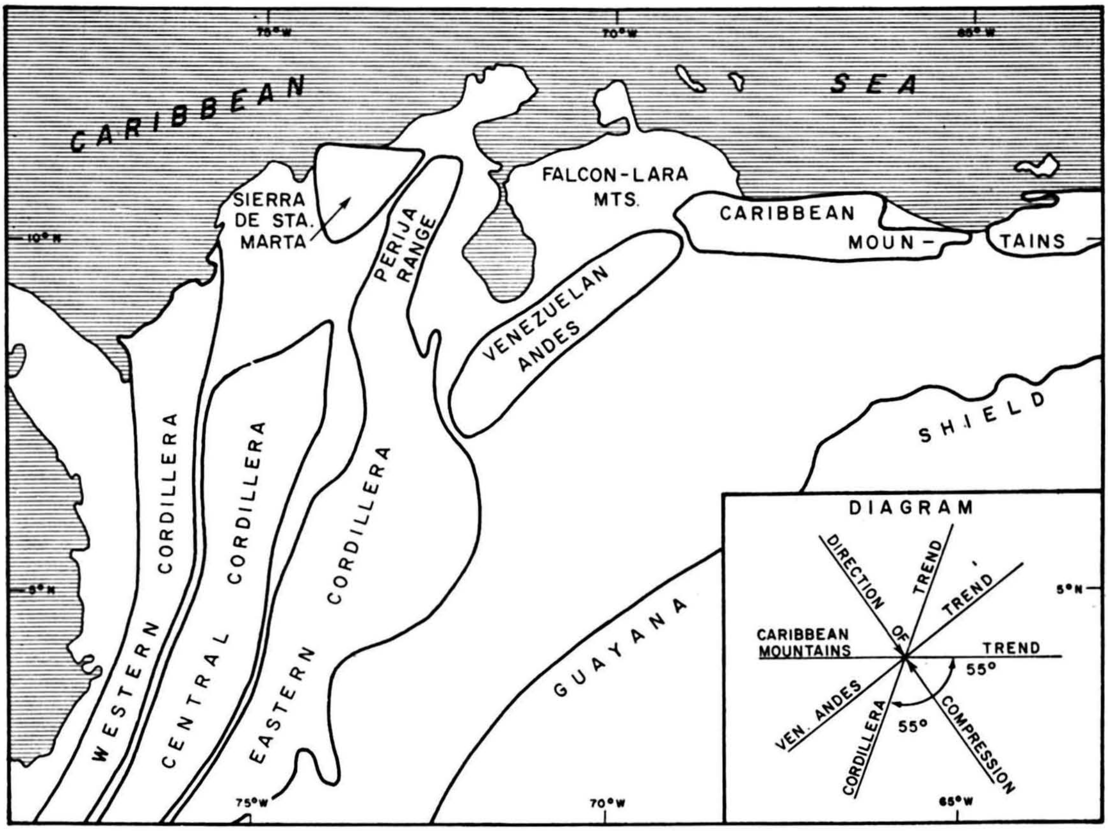


Fig. IX – 1. Possible direction of the compressive orogenic stress in Venezuela and Colombia.

are at right angles to the direction of the compression, then it follows that this direction must change considerably from one range to the other. For example, the direction of the three Colombian Cordilleras is not the same, and their average direction differs by about 70° from that of the Caribbean Mountains (Fig. IX – 1).

However, it is possible to account for the observed different trends by a uniform compressive stress. Fig. IX – 1 shows that the obtuse angle between the average direction of the Colombian Cordilleras and the direction of the Caribbean Mountains is about 110°. From theoretical considerations, originally due to BIJLAARD, the angle between the direction of the compression and the orogenic belt where plastic deformation takes place is about 55° (BIJLAARD, 1951; VENING MEINESZ, 1954, 1955). The direction which halves the obtuse angle between the abovementioned directions in Fig. IX – 1, may then be considered as the direction of the compressive stress. Having found this direction, it is seen that the trend of the Venezuelan Andes is practically at right angles to this direction.

This explanation implies that the Venezuelan Andes have originated through shear fracture, but the Colombian Cordilleras and the Caribbean Mountains through plastic deformation which may or may not have been restricted to the initial phases of the deformation. The direction of compression shown in Fig. IX – 1 must therefore be considered as hypothetical.

c. *Wrench faults*

One other major tectonic phenomenon may also be considered here, namely the wrench faults (also called strike-slip faults or transcurrent faults) of Venezuela. Wrench faults are faults along which the relative movement is practically in the direction of the fault strike. They are practically vertical and hence appear on the geological map as nearly straight lines.

Theory establishes (ANDERSON, 1951) that for wrench faults to originate it must be assumed that the directions of the maximum and minimum principal stresses are horizontal and that the direction of the intermediate principal stress is consequently vertical. The orientation of the stress ellipsoid is therefore different from that required for shear fracture; there the direction of the minimum principal stress is vertical. ANDERSON (1951, p. 20) points out that in spite of this difference in the orientation of the stress ellipsoid, shear fractures (thrust faults) and wrench faults may nevertheless occur in association with each other. It is quite well conceivable that a large north-south pressure is contemporaneous with an east-west pressure which is only a little greater than the vertical pressure at a given depth. Thrusting (shear fracture) will then result. A slight decrease of the east-west pressure may then make it less than the vertical pressure and if the north-south pressure continues, there may be formation of wrench faults. The association of thrusting and wrench faulting is therefore possible and is in fact known to occur.

When the stress ellipsoid is oriented as required for wrench faulting, the planes of maximum shear stress are vertical and form angles of 45° with the direction of the maximum principal stress. The planes of actual wrench faulting, however, will form smaller angles with the direction of the maximum principal stress, though remaining vertical.

The magnitude of the actual angle (α) is again dictated by the angle of internal friction (φ) of the solid, so that

$$\alpha = \pm\ (45° - \varphi/2)$$

Taking as before for φ a value of 30° (HUBBERT, 1951) it follows that on the map the wrench faults should from angles of 30° with the direction of compression.

The theory of wrench fault tectonics has been greatly advanced by MOODY and HILL (1956) in a stimulating paper. These authors develop the hypothesis that anticlinal folds, thrust faults, and wrench faults can be generated as a result of movement on a large wrench fault such as the San Andreas fault of California. Extension of this concept leads to the conclusion that for any given tectonic area, at least eight directions of wrench faulting (as well as four directions of folding and/or thrusting) can be distinguished.

MOODY and HILL advance the idea that wrench-fault tectonic systems exist in various areas of the earth and that they are aligned systematically over large portions of the earth's crust. Eight such principal wrench fault directions are defined. They conclude that the pattern may have resulted from stresses which are oriented essentially north-south and have been acting in nearly the same direction throughout much of crustal history.

These authors further conclude that major wrench faults constitute a fundamental type of yielding in the crust, and discuss the formation of geosynclines and islands arcs (amongst other topics) in terms of these ideas.

It may be useful to discuss the bearing these ideas have on the explanation advanced here for the structure of the Venezuelan Andes. It will be clear that the Venezuelan Andes are not essentially due to wrench faulting. The plane of a wrench fault is nearly vertical and the relative movement of the two crustal blocks separated by the wrench fault is essentially in the direction of the strike. The inferred major fault plane of the Venezuelan Andes, however, dips so as to form an angle of at least 45° and probably as much as 60° with the vertical.

For similar reasons the suggestion presented by MOODY and HILL (1956, p. 1243) that negative and positive isostatic anomalies associated with island arcs arise from the juxtaposition of rocks of greatly different density by means of large-scale wrench faulting, is rejected. The geophysical analysis of the Indonesian archipelago (VENING MEINESZ, 1948, 1954, 1955) shows, departing from a large body of observational facts, that these anomalies are essentially the result of crustal compression.

Moody and Hill's principles of wrench fault tectonics have been applied by ALBERDING (1957) to the system of principal faults of Northern Venezuela and Trinidad. Alberding's valuable maps include earlier data on wrench faults published by ROD (1956 a) and O. RENZ (1956).

MOODY and HILL concluded that, for any given tectonic area, at least eight directions of wrench faulting and four directions of folding and/or thrusting can be expected. Hence it is not difficult, as MOODY and HILL themselves have pointed out (1956, p. 1243) to fit any observed direction into the hypothetical pattern. This being so, it becomes necessary to apply the analysis very critically.

In Alberding's analysis, the direction of the primary compressive stress has a direction N 15° W – S 15° E. At right angles to this direction runs the primary thrust and fold direction. The validity of this direction must be questioned, as the observational evidence for this direction is very meagre indeed, as will be seen from Alberding's data.

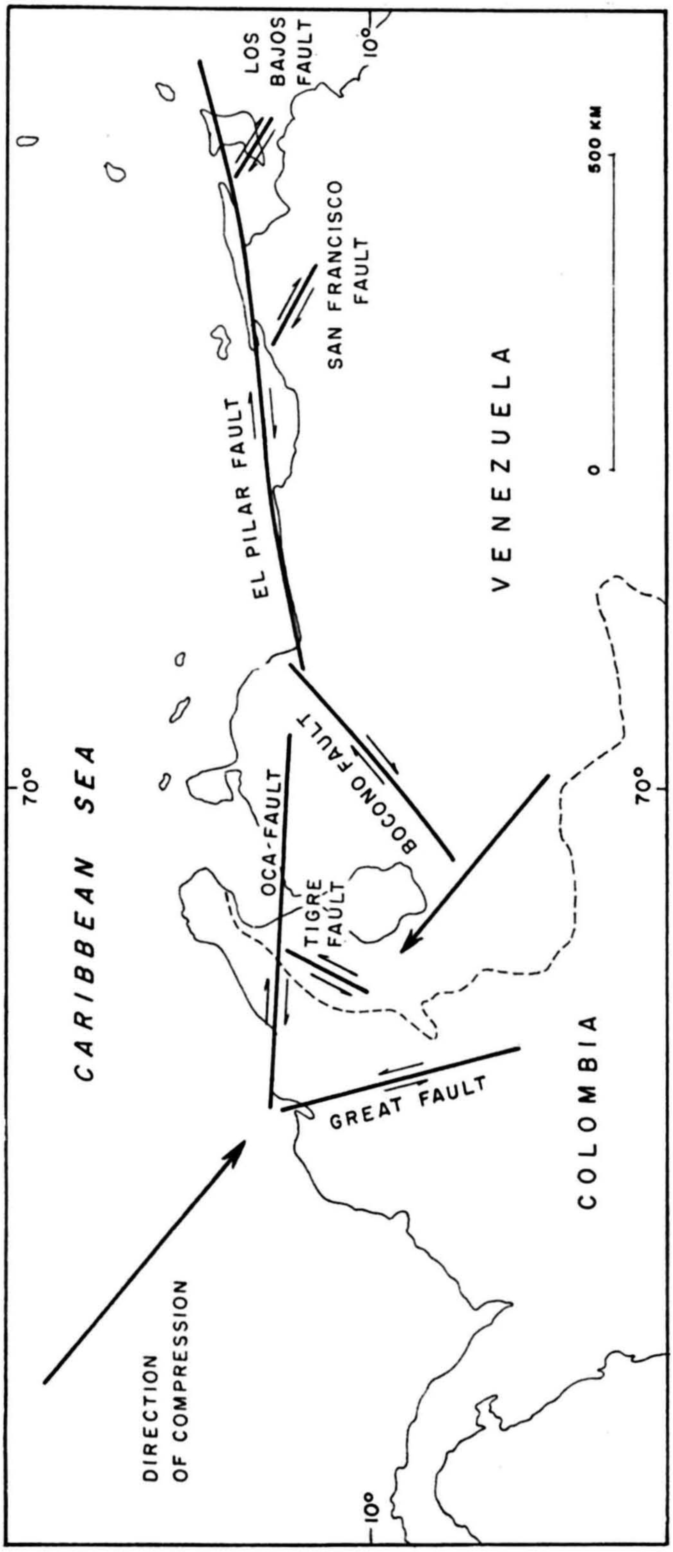


Fig. IX – 2. Wrench faults of Venezuela and Colombia. Based on data from ALBERDING (1957).

Another point upon which Alberding's analysis may be contested, is that the 1st order wrench faults are so poorly expressed. The 1st order left lateral wrench fault is represented by the Tigre fault, a minor wrench fault compared with others. The 1st order right lateral wrench fault direction is represented by the Los Bajos fault in Trinidad and the San Francisco fault in northeastern Venezuela, both minor faults (cf. Fig. IX – 2). On the other hand, the best established wrench fault of Venezuela (the Oca or Paez fault which runs approximately east and west to the north of the Sierra de Santa Marta and the Perija Range) is only a right lateral wrench fault of the 2nd order. The Great Fault of Colombia, also an important wrench fault, in only a 2nd order left lateral fault. The Bocono fault is of the 3rd order (right lateral).

Finally, it should be pointed out that, according to Moody and Hill's principles of wrench fault tectonics, second order wrench faults should terminate at the first order fault, third order faults at the second order fault, etc. This is so because second order wrench faults are manifestations of stress reorientation in one fault block and need not have counterparts in the fault block on the other side of the primary fault. Hence, in Alberding's interpretation, the Oca fault and the Great Fault of Colombia should terminate at the Tigre fault, which is not as observed.

These considerations make Alberding's analysis unsatisfactory and a different interpretation is therefore suggested here. This interpretation assumes that the primary thrust and fold direction is that of the shear fracture of the Venezuelan Andes. The primary compressive stress is thought to be at right angles to this direction, and hence to be practically identical with the direction of the orogenic compressive stress in Fig. IX – 1. The 1st order left and right lateral wrench faults are thought to be represented by the Great Fault of Colombia and the Oca (Paez) – El Pilar faults respectively (Fig. IX – 2). The angle between these fault directions is about 70°, not too different from the angle of less than 90° and probably as low as 60° required by theory (Alberding, 1957, Fig. 2, shows an angle of 60°). The relative movements along these faults are in agreement with the suggested direction of the primary compressive stress. The Tigre fault is then a 2nd order left lateral wrench fault terminating against the Oca fault. The Bocono fault is a 2nd order right lateral wrench fault terminating against the Great Fault of Colombia. The Los Bajos and San Francisco faults, in this interpretation, are 2nd order right lateral wrench faults terminating against the El Pilar fault.

The direction of both the orogenic compressive stress (Fig. IX – 1) and the primary compressive stress responsible for wrench faulting (Fig. IX – 2) is about N 55° W – S 55° E.[1]) This is an effective argument,

[1]) Professor F. A. Vening Meinesz has kindly informed the authors that the results of his latest gravity expedition at sea (southwest of the Isthmus of Panama and between Panama and Curaçao) also yield an approximately NW–SE direction of compression.

against Moody and Hill's thesis that wrench fault tectonic systems are aligned systematically over large portions of the earth's crust and may have resulted from stresses which are oriented essentially meridionally. The Venezuelan wrench faults fit remarkably well into Moody and Hill's wrench fault tectonic system, but they show that the primary compressive stress was not oriented in an essentially north and south direction.

X. DISCUSSION OF SOME GENERAL OROGENIC THEORIES

a. *General remarks*

In marked contrast with the West Indies, the Venezuelan Andes have not received much special attention from students of orogenic phenomena. Nevertheless, the Venezuelan Andes and their gravity field are of considerable interest in this respect. For that reason the orogenic theories of Vening Meinesz (buckling hypothesis) and of van Bemmelen (undation theory) will be considered in the light of the inferred deeper structure of the Venezuelan Andes and adjacent basins.

b. *Comparison of the Venezuelan Andes and the Alps*

It has already been pointed out that, if orogeny is considered to be a process due to mechanical failure of the earth's crust under horizontal compression, there are two main theories of how this failure takes place. One of them is the plastic buckling hypothesis of Vening Meinesz and Bijlaard, the other the shear fracture hypothesis of Gunn.

VENING MEINESZ (1954, 1955) has shown that the plastic buckling hypothesis can account for the major features of the gravity field of the Indonesian archipelago. The same author has also pointed out (VENING MEINESZ, 1948, 1954) that the Alps are a good example of a mountain range originating through plastic buckling of the crust. On the other hand, it would seem that the Venezuelan Andes originated through a process in which shear fracture was the controlling factor. Consequently, both plastic buckling and shear fracture may be possible controlling factors in orogeny. There are, in fact, strong indications that both plastic buckling and shear fracture do occur at different places in the same belt of deformation. The best example is the crustal deformation described by VENING MEINESZ (1948, pp. 72–74) in the tectonic belt west of Sumatra which shows striking similarities with the deformation inferred here for the Venezuelan Andes. Elsewhere in Indonesia, however, the deformation is best accounted for by the buckling hypothesis.

For out present purpose, it is thought that a comparison of the Venezuelan Andes and the Alps, even though only in very general terms, may be illuminating. Attention will thus be drawn to a number of important differences. However, it should not be forgotten that plastic buckling and shear fracture have much in common. Both hypotheses account for orogeny as due to mechanical failure of the earth's crust under compressive stress. Both therefore involve the same orogenic forces and both can therefore be derived from the same ultimate cause of these forces, namely thermal contraction of the earth or convection currents in the mantle.

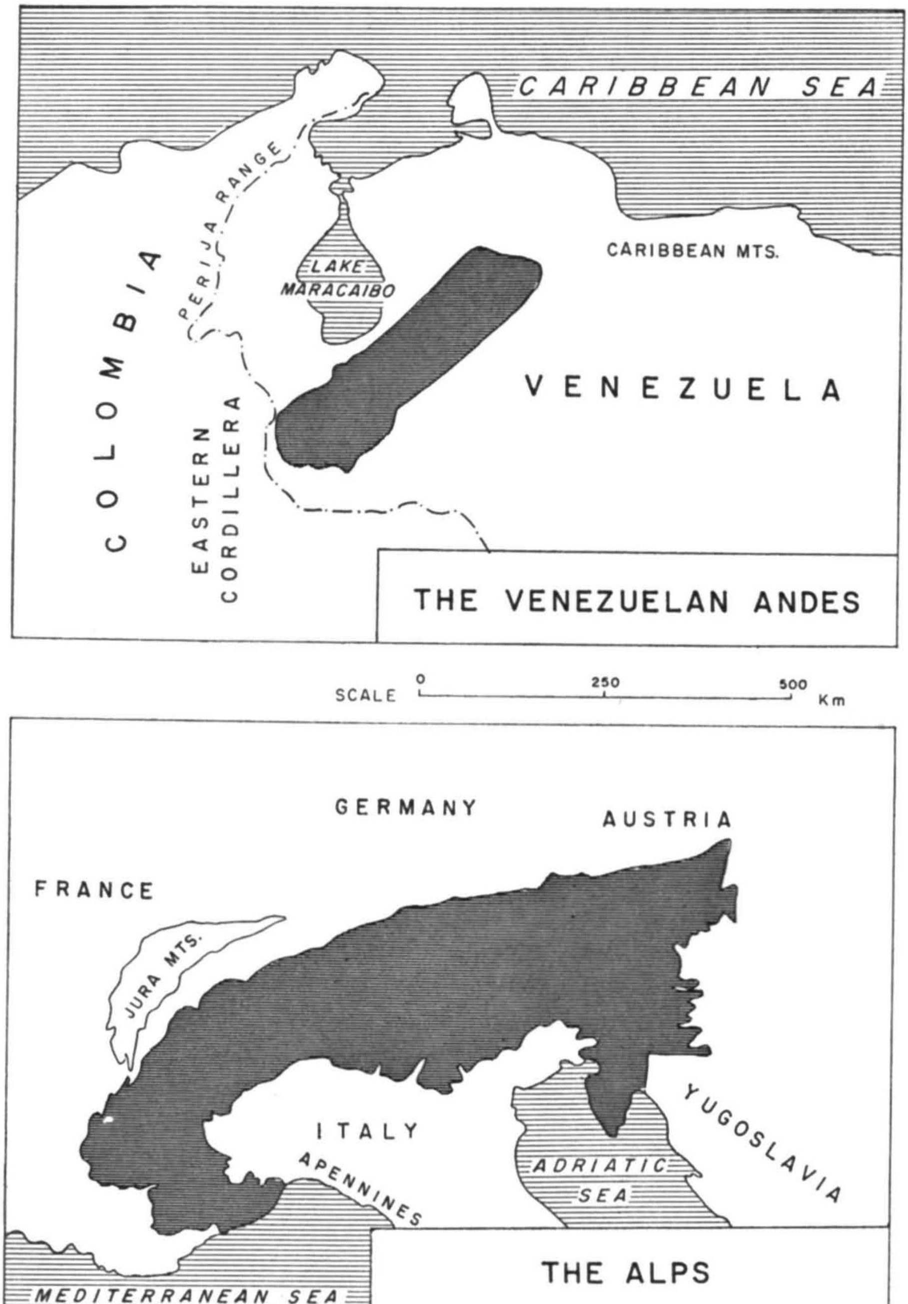


Fig. X – 1. The Venezuelan Andes and the Alps on the same scale.

On the map, there are striking differences in appearance between the Alps and the (Venezuelan) Andes. The Andes form a straight mountain range, 400 km long and 100 km wide. The Alps are curved, wider, and much longer. There is no indication of one major fault or fault zone determining their outline on the map. Fig. X–1, showing both ranges on the same scale, illustrates the difference in general appearance.

Structurally, there are very significant differences. The Alps are characterized by the presence of nappes. The Pennine nappes in particular are convincing evidence that strong lateral compression resulted in predominantly plastic deformation with considerable horizontal movements. The Venezuelan Andes have no nappes; the tectonic style is characterized by block faulting. The enormous difference in tectonic style is well brought out if a comparison is made of sections across the Alps such as the well-known sections of E. ARGAND and R. STAUB reproduced by COLLET (1927, Plate XI) and the sections across the Venezuelan Andes in MILLER *et al.*, (1955).

From gravity measurements it is found that the topography of the Alps is locally compensated; there is a light root situated under the mountain range. This points to the conclusion that the earth's crust in the Alps suffered plastic deformation (plastic buckling), and that, when isostatic equilibrium began to be established, the deformed belt was sufficiently plastic to reach a state of local isostatic compensation. The Venezuelan Andes, on the other hand, present a fundamentally different gravity picture. The negative isostatic anomalies are found over the Maracaibo Basin and at the northwestern edge of the range; the root is displaced towards the basin and is not situated underneath the mountain range.

Another point of difference which may be significant is that it would appear that the amount of crustal shortening in the Alps computed from the gravity data is at least one-and-a-half times to twice that computed for the Andes. Figures much larger than those derived in the preceding chapter may be obtained by making different assumptions about the crustal structure and the amount of sediments to be taken into account, but the figure for the Alps will remain the larger one for any given set of assumptions.

The hypothesis advanced here, namely that the Alps and the Venezuelan Andes originated by different types of mechanical failure, has an important consequence. If the Alps originated by plastic buckling of the earth's crust, it must be thought that the mountain range came into being through the subsequent isostatic uplift of the root of plastically deformed crustal material. If the Andes came into being by shear fracture of the earth's crust, it must be inferred that the mountain range was not formed by isostatic uplift after deep depression, but emerged as a direct result of one crustal block being thrust over another. The Andes rocks may therefore never have been below their pre-orogenic normal equilibrium position.

The great differences between the Alps and the Venezuelan Andes appear to agree very well with DE SITTER's (1956 a, pp. 471–482) discussion of the great diversity in size and structure among mountain chains, and of the contributing factors causing this diversity.

c. *The undation theory*

The conclusions concerning the deeper structure of the Venezuelan Andes drawn from the present study of the gravity field of western Venezuela are partly conditioned by the initial assumptions. These assumptions are that there exists a light elastic crust floating on a dense weak substratum, and that the large-scale tectonic features of this crust are the result of lateral compressive stresses acting in the crust.

Orogenic hypotheses starting from different assumptions are, however, also being advocated. The undation theory of R. W. VAN BEMMELEN (1949, 1954, 1958) is at present the best known representative of this group.

According to VAN BEMMELEN, the earth's crust consists of two layers: an upper granitic or sialic layer, of about 18 km thickness, and a lower intermediate or salsima layer of about 22 km thickness. Densities of 2.7 and 3.0 are assigned to these layers. The salsima layer is underlain by a heavy substratum (sima) of density 3.2.

The intermediate layer is thought to be chemically unstable, and may differentiate into on the one hand granitic magma that will form an "asthenolith" of light matter (density 2.5) at the base of the upper layer and on the other hand a heavy fraction, termed "neo-sima" (density 3.1). The light root eventually pushes up the overlying sialic layer and thus creates a mountain range on the surface. The asthenolithic root matter is thought to corrode and migmatize the upper layer of the crust at its lower surface. The upward movement of the mountain range is volumetrically compensated by subsidence of the adjacent areas, thus creating basins (side deeps). The heavy neo-sima fraction is thought to settle and spread out along the boundary between intermediate layer and substratum. The splitting up of the intermediate layer into a light and a heavy fraction is initiated by geosynclinal subsidence. The geosynclinal subsidence itself is thought to be due to geochemical processes taking place at great depth in the earth.

In its original form (VAN BEMMELEN, 1949, 1954) the undation theory did not admit lateral compressive forces as a cause of orogeny. This has led to a number of objections which will be formulated below.

In the first place, it will be clear that, in order to account for a mountain range, the undation theory must assume that there is a light asthenolithic root situated right underneath the range. The light root material therefore must produce a gravity effect which is approximately symmetrical on a cross-section. The observations establish, however, that the gravity field of the Venezuelan Andes is asymmetrical to the extent that the most negative part of the Bouguer anomalies lies northwest of the range, in the Maracaibo Basin. Even if one allows for the asymmetry caused by the Maracaibo Basin being deeper than the Barinas-Apure Basin, it appears that the residual effect due to the root is still asymmetrical and centers on the northwestern edge of the Andes (Fig. VII – 1).

A second point concerns the local isostatic anomalies (Fig. VIII – 4). The undation theory postulates that orogenic movements are reactions, under the influence of gravity, to density changes in the crustal materials brought about by geochemical processes. Upward movements are hence necessarily restricted to parts of the crust which are underweight, as shown by negative isostatic anomalies. Downward movements are similarly necessarily restricted to crustal tracts which are overweight, as evidenced by positive isostatic anomalies. It is admissible to postulate that there are time lags between a crustal column becoming over- or underweight (due to geochemical processes), and the following downward or upward movements. However, there is no possibility of areas of positive isostatic anomalies moving up or areas of negative isostatic anomalies going down. Yet, the observational evidence shows that the essentially upward moving Venezuelan Andes have positive isostatic anomalies and that the essentially downward moving Maracaibo Basin has negative isostatic anomalies.

A third point concerns the wrench faults of Venezuela and Colombia discussed in Chapter IX. There it was made plausible that these wrench faults are intimately associated, in the direction of their causative compression, with the origin of the Venezuelan Andes. This suggests the possibility of strong lateral compression in the earth's crust.

These and related objections against the original undation theory have led VAN BEMMELEN (1958), in a discussion of the Caribbean area, to adopt the concept of lateral compression in the earth's crust as a cause of orogeny in this part of the world.

The particular interest of the gravity field of the Venezuelan Andes and adjacent basins lies, therefore, in the fact that its analysis, inevitably it would seem, leads to the concept of lateral compression as a cause of orogeny.

For a more general discussion of these topics in relation to the gravity field and structure of northern South America and the West Indies the reader is referred to papers by VAN BEMMELEN (1958) and HOSPERS (1958).

Once lateral compression is admitted as a primary cause of orogeny, there is less reason to assume that light differentiation products still play a significant role in the pushing up of the Venezuelan Andes as VAN BEMMELEN (1958, pp. 15, 16) does. The total absence of hypodifferentiation cannot be conclusively demonstrated, but the strongly positive isostatic anomalies of the Venezuelan Andes indicate that if hypodifferentiation has taken place at all, its significance is certainly negligible compared with that of the lateral compression. This is so because the isostatic anomalies reflect the total mass in the crustal columns. Even if there were heavier parts (basic and ultrabasic fronts) in the substructure of the Venezuelan Andes, cancelling the gravity effect of a lighter mass (asthenolithic root), the evidence of the positive isostatic anomalies still shows that, as a whole, the crustal column in the Venezuelan Andes is far too heavy. Consequently, the Venezuelan Andes cannot have been pushed up by a light root, as this would be expressed by negative, or in the case of exact floating equilibrium, by zero isostatic anomalies.

The present discussion, therefore, leads to doubts that hypodifferentiation has taken place in the area under discussion. However, these doubts must not be taken to extend to other important aspects of the undation theory, such as secondary tectogenesis and the importance of geochemical processes in general.

XI. SEISMICITY OF THE VENEZUELAN ANDES

a. *Instrumental data*

Instrumental data on earthquakes up to 1952 have been organized by GUTENBERG and RICHTER (1954). Their Figs. 10 (Caribbean region), 11 (South America and adjacent Pacific), and 27 (Atlantic Ocean) show the available data for Venezuela.

It appears that there are no known deep-focus earthquakes (focal depth greater than 300 km) within Venezuelan territory. The recorded intermediate earthquakes (focal depth between 70 and 300 km) are of class c (magnitude 6.0–6.9) or of lesser magnitude. The recorded shallow earthquakes (focal depth less than 60 km) are also of class c or of lesser magnitude. (Class c earthquakes are shocks that are not recorded all over the earth but are well recorded up to a distance of 90° or 10,000 km over the surface of the earth).

The epicentres of the intermediate shocks are situated between Trinidad and Venezuela (two), and in the Caribbean Mountains of northeastern Venezuela (one). The epicentres of the shallow shocks (of which there are about a dozen inside Venezuelan territory) are for the greater part situated in or near the Venezuelan Andes and the Caribbean Mountains. Three of them are situated outside these mountain ranges; they are aligned along the meridian at 71° West. As GUTENBURG and RICHTER (1954, p. 11) point out, this is a spurious alignment due to the fact that the latitudes and longitudes of epicentres are usually assigned to the nearest full, half, or quarter degree.

b. *Historical data*

Historical data on Venezuelan earthquakes between 1530 and 1939 have been studied by CENTENO-GRAÜ (1940). His study shows that the historical Venezuelan earthquakes have mainly been felt in the Venezuelan Andes and in the Caribbean Mountains. In these mountain areas all the great earthquakes have taken place, with the exception of the destructive earthquakes of Maracaibo (1849), Guanare (1888) (Guanare is situated in the Llanos just outside the Venezuelan Andes in the State of Portuguesa), and Mapararí (1910) (Mapararí is situated in the Falcon mountains area).

Historical data cannot give a reliable idea of the distribution of earthquake epicentres because they are much influenced by the distribution of people. It must therefore suffice to conclude that the historical data suggest the same as the instrumental data clearly demonstrate, namely that the Venezuelan Andes and the Caribbean Mountains are seismically active regions. In the rest of Venezuela the seismicity is far lower.

c. *Geographical distribution of earthquake epicentres in Venezuela*

Rod (1956 b) has published a fault map of Venezuela on which are also shown the instrumentally determined epicentres (from Gutenberg and Richter, 1954) discussed above, as well as the position of cities and towns where shocks were felt (based on the historical data of Centeno-Graü, 1940).

Rod cautiously suggests that the seismicity of northern Venezuela might be related to movements along the big wrench faults depicted on this map. This caution is, of course, well justified as in the present instance neither the macroseismic nor the instrumental data are sufficiently accurate to establish such an association.

XII. CONCLUSIONS

1) The gravity field of the Maracaibo Basin is thought to be due to the negative gravity effect of a downwarp of the crust (which causes the heavy substratum to be replaced by lighter crustal matter) combined with the effect of light Post-Eocene sediments (taken as replacing matter of standard crustal density).

2) The same is thought to be true for the Barinas-Apure Basin.

3) Underneath the Venezuelan Andes there is an asymmetrical mass distribution.

4) This asymmetry points strongly to the conclusion that the southeastern part of the crust was thrust over the northwestern part. The major thrust fault is probably situated along the northwestern edge of the Venezuelan Andes, the mountains having been thrust to the northwest over the Maracaibo Basin.

5) It is thought that the controlling factor in the origin of the Venezuelan Andes and the adjacent basins was the development of a shear fracture, as postulated by Gunn. Some plastic deformation, however, must also have taken place.

6) Gunn's shear fracture hypothesis adequately explains the width of the total belt of deformation and the width of the Maracaibo Basin. It predicts less accurately the width of the Venezuelan Andes. This hypothesis also accounts very well for the contrary movements of the Venezuelan Andes on the one hand and the Maracaibo Basin on the other.

7) There is no difficulty in reconciling the isostatic anomalies with Gunn's shear fracture hypothesis.

8) It is thought that lateral compressive stresses began to bring about permanent deformation by a beginning shear fracture in late Eocene – early Oligocene times. The strong uplift of the Venezuelan Andes and the contemporary subsidence of the Maracaibo Basin in Mio-Pliocene time is thought to represent the result of increased compression.

9) The amount of crustal shortening during the orogeny in the Venezuelan Andes is estimated to be at most of the order of 50 km.

10) Studies of the direction of the orogenic stress are unsatisfactory as the time element has to be left out of consideration. However, a possible direction of orogenic stress is at right angles to the Venezuelan Andes. This could produce a shear fracture there, and initial plastic deformation in the Colombian Cordilleras and the Caribbean Mountains which, on

the map, form an angle of 55° with this direction. The angle of 55° is predicted by theory. A similar direction follows from an analysis of wrench faults.

11) Comparison of the Venezuelan Andes with the Alps brings out pronounced differences in general appearance, structure, and gravity field, as well as an appreciable difference in the inferred amount of crustal shortening. An attractive explanation is that the Alps originated mainly through plastic buckling, the Venezuelan Andes mainly through shear fracture.

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