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INTERPRETATION OF GRAVITY ANOMALIES ON THE WESTCOAST OF SOUTH AMERICA AND IN THE CARIBBEAN

observed o/b U.S.S. CONGER by
P. C. WUENSCHEL and G. R. HAMILTON
(LAMONT GEOLOGICAL OBSERVATORY)

AND

THE PUERTO RICO TRENCH; TWO TYPES OF DEEP OCEAN TRENCHES

by F. A. VENING MEINESZ

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I. INTERPRETATION OF GRAVITY ANOMALIES ON THE WESTCOAST OF SOUTH AMERICA AND IN THE CARIBBEAN

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The cruises of U.S.S. Conger took place in September and October 1947. Prof. Dr. MAURICE EWING kindly inserted the gravity results in the Memorial Volume offered to the writer in 1957 on the occasion of his retiring as professor of Geophysics and Geodesy. Prof. Dr. W. A. HEISKANEN kindly provided the isostatic reduction of the results according to the Airy-Heiskanen method for a crustal thickness T of 30 km.

It is a great privilege to the writer thus to be able to study at his leisure this exceptionally important observation material. He should not want in this paper to omit expressing his sincere thanks to Professor EWING for this privilege and also to all who made these observations possible, to the Captain, Officers and crew of U.S.S. Conger, and especially to the makers of these observations, Dr. WUENSCHEL and Dr. HAMILTON. The writer is familiar with the trouble it takes to all concerned to do gravity work at sea in submarines, particularly if in the different profiles the stations follow each other so closely as has been the case. So, in using this precious scientific material, he is deeply conscious of the great service rendered by so many. In the following paper he indicates the different gravity stations by the serial numbers mentioned in the above mentioned Memorial Volume.

By studying the gravity profiles on the westcoast of South America and in the Caribbean the writer can check the hypothesis about the system of mantle convection-currents in that area, which he published in "Pattern of Convection-currents in the Earth's Mantle" *); in putting forward this hypothesis he did not make use of these gravity profiles. The result of this check shall prove to be remarkably successful, and so this is obviously strongly in favour of it.

The hypothesis assumes that the South American continent is affected by a mantle convection-current which rises under the Pacific ridge running from near Chiloé Island at an azimuth of about N60°W towards the Mid-Pacific ridge. Below the crust this current, in the present period at least, only seems to sweep to the NNE, and it would, therefore, have an azimuth of about N30°E. It may be supposed to have had, and still to have, a strong effect on the Andes and on the accompanying troughs along the coast. With regard to these effects we can divide the Andes in

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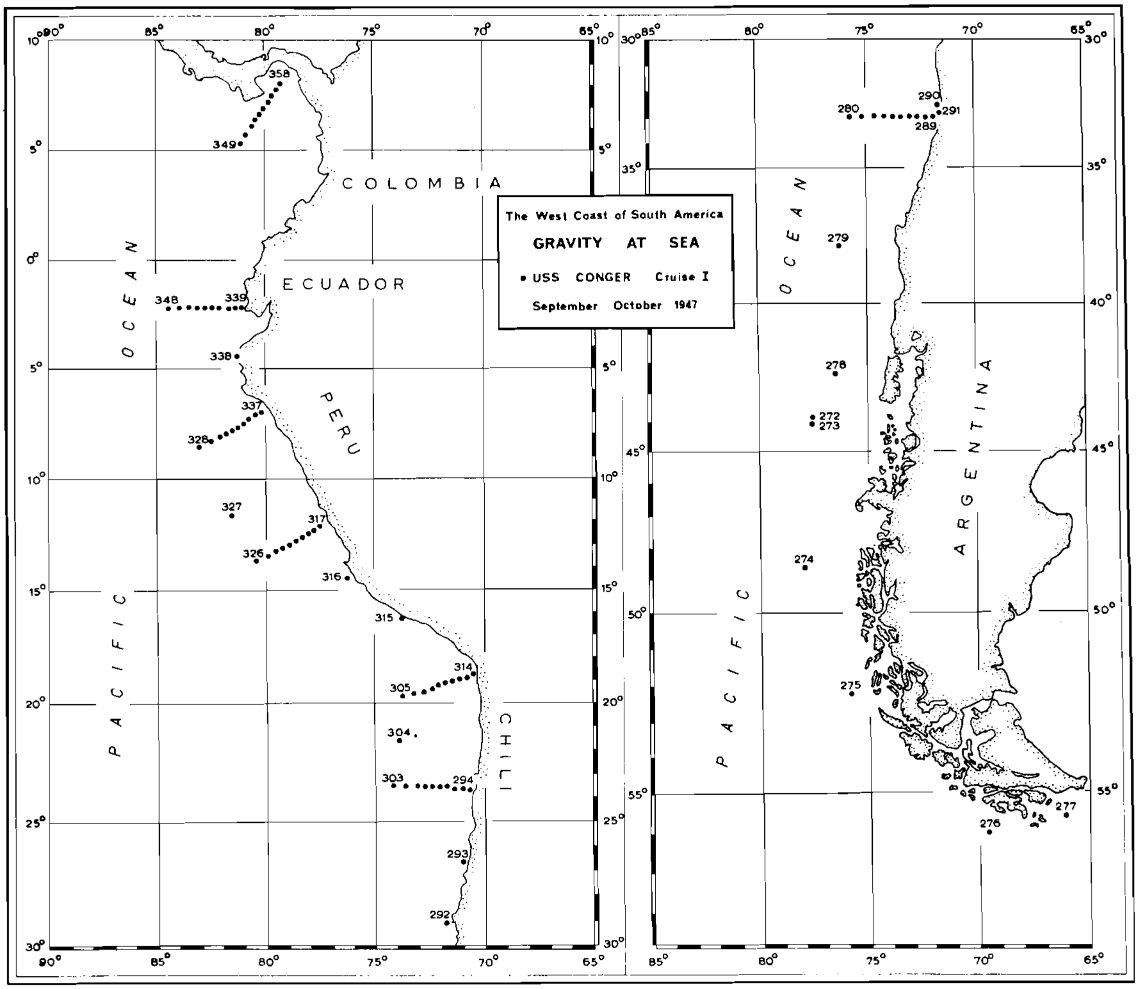
*) Proc. Kon. Ned. Akad. v. Wetensch., Ser. B, 65, No. 2, Amsterdam 1962.



Map 1

three more or less straight parts, the part south of Arica, the part between Arica and Payta, and the part to the NNE of Payta.

The first part, having an azimuth of about N5°E, makes an angle of about 25° with the direction of the subcrustal current. This angle points to dextral shear along a crustal faultplane in the direction of the Andes; it checks with the theory of shear, applied to geology by CHAMBERLIN and SHEPARD *), and further developed by ANDERSON **), HUBBERT ***) and HAFNER ****).

The angle enclosed between the directions of the faultplane and the mantle-

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*) See e.g. ST. AMAND and ALLEN, Strike-slip faulting in northern Chile, Bull. Geol. Soc. Am., 1960, p. 1965.

**) ANDERSON, E. M., The dynamics of Faulting, 1st Ed. 1942, 2nd Ed. 1951, Edinburgh and London, Oliver and Boyd.

***) HUBBERT, M. KING, Mechanical basis for certain familiar geologic structures, Bull. Geol. Soc. Am., v. 62, 1951, pp. 355–372.

****) HAFNER, W., Stress distributions and faulting, Bull. Geol. Soc. Am., v. 62, 1951, pp. 373–398.

current indicates that this shear movement has to be accompanied by an overriding, which evidently must be such that the eastern crustal block overrides the western block. This explains the high Andes range and the adjoining deep ocean trenches. It also explains that nearly all Andean earthquakes occur to the north of the island of Chiloé. The recent disastrous earthquake, of which the centre was situated near Tolten, has been accompanied by an enormous dextral displacement of probably more than 6 m.

The writer should not want here to go deep into the problem how in an older period of the earth's history the part of the Andes south of the island of Chiloé can have come into being. It appears likely that this came about by a subcrustal current-system similar to the present one but situated further to the south. A shift of the polar axis with regard to the crust, caused by a rotation of the whole crust with regard to the earth's interior could easily have happened. This hypothesis would fit a good many other data also. We may finish our short discussion of this problem by remarking that the point here raised gives a new argument in favour of polar shift.

The two gravity profiles, given by Figures 1 and 2, at about right angles to this part of the Andes and at latitudes of about 33°02'S and 23°40'S respectively, are in good harmony with our view about the type of crustal mechanism working in this

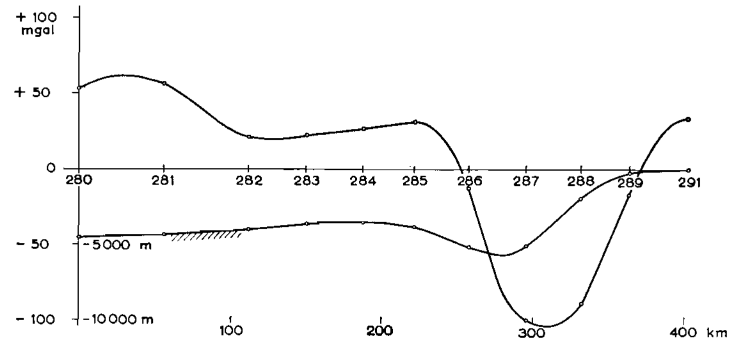

Figure 1. Gravity profile on the Westcoast of South America at 33°02'S (lat. of the coastal station); see map 1

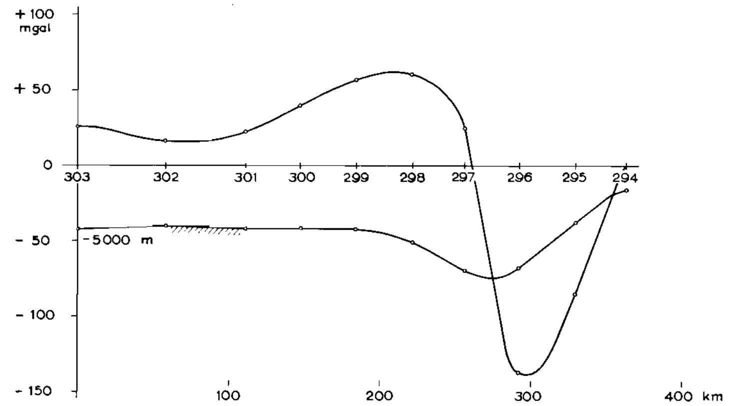

Figure 2. Gravity profile on the Westcoast of South America at 23°40'S (lat. of the coastal station); see map 1

area. The greatest negative anomaly is found below the eastern slope of the ocean trench, where the overriding must cause a root of light crustal matter. The great number of volcanoes in this part of the Andes, which are all more or less in line with each other, also fits our hypothesis. We can easily account for them by the presence of the great crustal faultplane, along which the dextral shear movement takes place. Such a movement may easily offer occasions for the magma to escape upwards.

Of the second part of the Andes, between Arica and Payta, the whole north-western part, between Cuzco and Payta, i.e. about two thirds of its length, encloses an angle of 55° with the direction of the great mantle current; it has an azimuth of about N25°W. This leads to the hypothesis, that here the crust is subject to plastic downbuckling, in the same way as this is the case in the central parts of island-arcs. The writer will not go deep into this type of crustal deformation; he may refer to many previous papers on this subject *). He may, however, mention that this phenomenon leads to the formation of a geosyncline, and that in this belt usually strong folding and overthrusting of the surface layers must occur. It is interesting, however, that the whole part of the Andes between Cuzco and Arica has a different direction; it has an azimuth of about N55°W. It, therefore, encloses an angle of about 85° with the direction of the supposed convection-current in the mantle. Is it possible to understand this different direction?

The writer thinks, that tentatively the following attempt to an explanation might be made. In this part of the Andes the shear movement along the great faultplane in the first part of the Andes must lead to large crustal stresses and deformations. Near Arica the western block advances northwards with regard to the eastern block. This advance may well be larger than what corresponds to the shortening, possible in the geosyncline of the second Andes part. If we assume that this excess of the relative velocity amounts to 5 cm/year, ten million years would already lead to a total relative shift of 500 km. So if we could reconstruct the position of the Andes near Arica before that period by displacing this part over 500 km to the south, we should find it in line with the Andes between Payta and Cuzco, and then this whole second Andes part would enclose with the direction of the mantle-current the above-mentioned angle of 55°. We should, therefore, feel inclined to assume that the great relative shift in the first part of the Andes, i.e. the part south of Arica, would lead to a northward shift of the different cordillera ranges between Arica and Cuzco.

Some support for this rather bold view might perhaps be found in curious features in the gravity profiles Figs. 3, 4 and 5 of which the coastal stations have the latitudes of 18°48'S, 12°16'S and 7°02.5'S respectively. In profile No. 3 the belt of negative anomalies is still situated under the downward slope between the coast and the trench, but is it broader than in the profiles No. 1 and No. 2; the profile shows a bulge towards the right. In profile No. 4 this bulge has developed in a second downward

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*) VENING MEINESZ, F. A., Plastic Buckling of the Earth's Crust: The Origin of Geosynclines; Geol. Soc. Am., Special Paper 62, "The Crust of the Earth", pp. 319–330.
VENING MEINESZ, F. A., Indonesian Archipelago: a Geophysical Study; Bull. Geol. Soc. Am. v. 65, 1954, pp. 143–164.
HEISKANEN, W. A. and VENING MEINESZ, F. A.; The Earth and its Gravity Field, Chapters 10A and 10C, Mc.Graw-Hill, New York, Toronto, London, 1958.

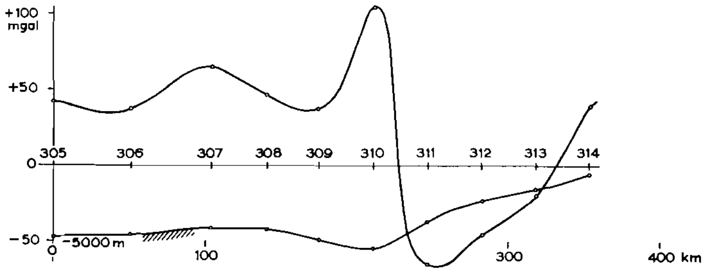

Figure 3. Gravity profile on the Westcoast of South America at 18°48′S (lat. of the coastal station); see map 1

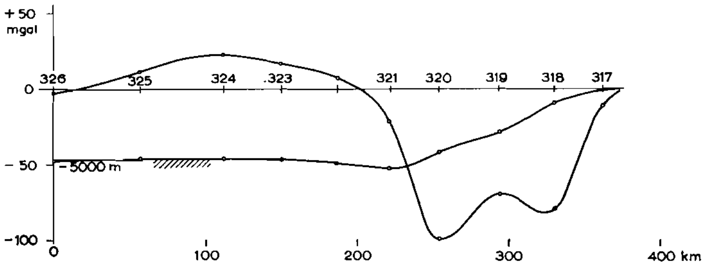

Figure 4. Gravity profile on the Westcoast of South America at 12°16′S (lat. of the coastal station); see map 1

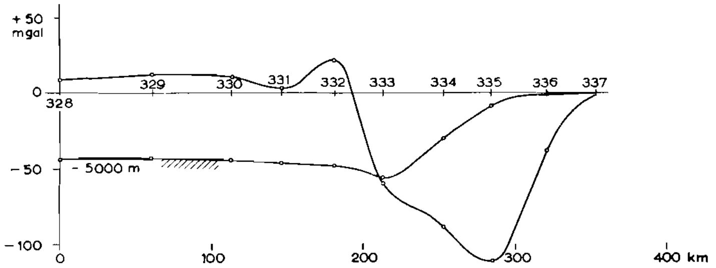

Figure 5. Gravity profile on the Westcoast of South America at 7°02′S (lat. of the coastal station); see map 1

wave, and so the belt of negative anomalies, though still entirely located below the continental slope, shows two negative maxima, of which no doubt that to the left is the continuation of the negative maximum of profile No. 3. In profile No. 5 the downward wave to the right has come to full development, but the wave to the left only shows as a bulge. So we find that the downward wave, which must be interpreted as a downbuckling of the crust, is gradually disappearing towards the NNW and is replaced by another downbuckling belt nearer to the coast. We may perhaps see it in this way that the latter belt originally continued over the whole length of this second part of the Andes, but that the concentration of crustal matter in the SSE part, caused by the above mentioned compression, has rendered the crust too rigid for downbuckling and that here, consequently, the belt of plastic downbuckling has shifted towards the ocean side.

The hypothesis that in the SSE part of this Andes section the whole range has shifted northwards, obviously implies that the continental crust to the north of the range has given way by downbuckling. We may suppose that this shows at the surface by one or more folded ranges added to the range area. This seems indeed to be confirmed by the facts; the group of ranges north of Arica is clearly broader than the group of ranges between Cuzco and Payta.

Before leaving the Chilean part of the Andes, we may mention that in young palaeozoic times, and more recently, orogenic features came into being, diverging from the Andes towards the SSE and SE. We refer to the Sierra de Tandil and the Sierra de Ventana, which south of Buenos Aires reach the Argentinian eastcoast, they show young palaeozoic folding; we may also mention the Sierra de Olte and the Cañadon Grande showing jurassic folding, which via the Lago Musters reach the eastcoast north of Santa Cruz. We see that these chains, as also in South Patagonia and Tierra de Fuego the Andes themselves, have the same direction as the northwestern part of the Peruvian Andes, and that they, therefore, enclose an angle of about 55° with the direction of the supposed mantle-current.

So, if we assume that at the time of the folding of these chains the position of the poles was such, that the current could normally affect the crust in these areas, we may suppose that in these belts the crust was subject to plastic downbuckling and geosyncline formation, and that thus these chains came into being.

We shall now examine the third part of the Andes, between Payta and the Caribbean. In the first place we dispose of a gravimetric profile (Fig. 6) just north of the Gulf of Guayaquil. Besides, we can make use of the results of a gravity expedition of the Netherlands Geodetic Commission during which G. Bakker and L. Otto observed four gravimetric profiles between the Gulf of Guayaquil and the isthmus of Panama. The results of this expedition made o/b Hr. Ms. Submarine "Walrus" of the Netherlands Navy, have been published in Vol. V of "Gravity Expeditions" *), and these profiles have been inserted in this paper.

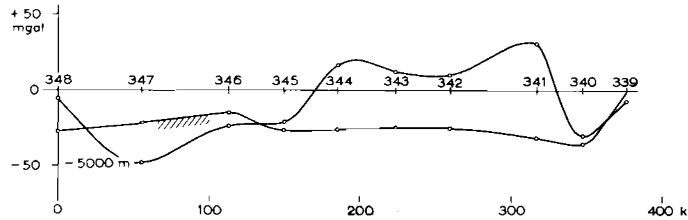

Figure 6. Gravity profile on the Westcoast of South America at 2°15′S (lat. of the coastal station); see map 1

The southern part, up to the equator, of this third Andine section has an azimuth of about N20°E; further north it splits up in three chains having azimuths between N20°E and N35°E. We see that this section of the Andes encloses a much smaller angle with the supposed direction of the mantle current than the first section. So we may assume that here also each chain is marked by a great faultplane through the crust, along which dextral relative displacement takes place, but that the over-

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*) Publication of the Netherlands Geodetic Commission, Kanaalweg 4, Delft, 1960.

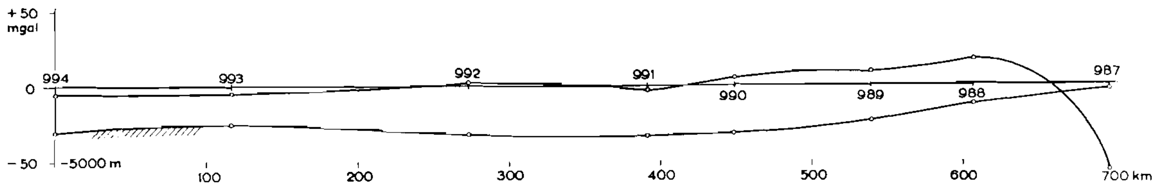

Figure 7. Gravity profile on the Westcoast of South America at 0°42′S (lat. of the coastal station); see map 2

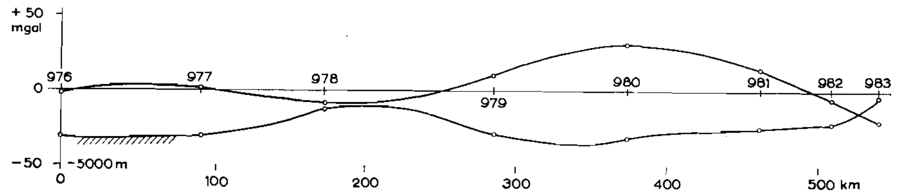

Figure 8. Gravity profile on the Westcoast of South America at 1°12′N (lat. of the coastal station); see map 2

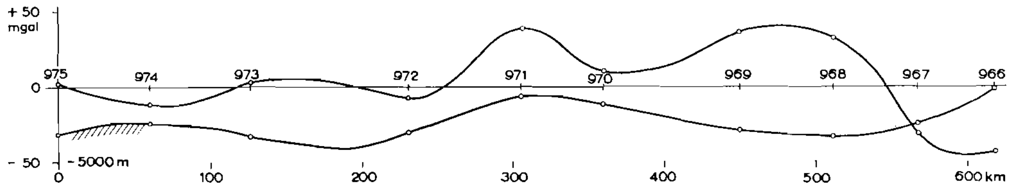

Figure 9. Gravity profile on the Westcoast of South America at 2°37′N (lat. of the coastal station); see map 2

riding of one side over the other is much smaller. If we put the angle between mantle current and chain at 10°, we may conclude that the overriding must be about three times less than that for the first Andes section.

This conclusion is in good harmony with the absence of deep troughs along this part of the South American westcoast and it also agrees well with the values of the negative gravity anomalies in the profiles. These values amount to —29 mgal for the profile given by Fig. 6 of the U.S.S. Conger expedition, and to —53, —20 and —42 mgal respectively of the three adjoining profiles of Hr. Ms. Walrus expedition, given in Figs. 7, 8 and 9. The mean of these four values is —36 mgal. This checks well with the fact, that the three profiles along the first Andes section, i.e. Figs. 1, 2 and 3, show negative maxima of —100, —139 and —68 mgal respectively, of which the mean is —104 mgal; the ratio is indeed near to 1 : 3.

This agreement gives a strong support to the hypothesis that the whole South American continent is affected by a great mantle-current system in a direction of N30°E. As it has already been mentioned, this hypothesis was put forward independent of the gravity results dealt with in this paper. It was based on the direction of the Pacific ridge running from the South American westcoast near the island of Chiloé towards the East Pacific Rise, and also on the crustal deformations in the Antilles area which point to a mantle-current system below that area in a direction of N35°E.

This convergence of data from three different sources of information gives reason to feel confident about the hypothesis. On the other hand it gives new confirmation of the viewpoint, nowadays so widely accepted, that the mid-ocean ridges are situated over rising mantle-convection-currents.

A further check of our hypothesis is given by the fourth profile of the Walrus expedition (Fig. 10), which is located further to the north, near Buenaventura. It shows a higher negative gravity anomaly, viz. —82 mgal, and this is in good harmony with the fact that from here the coast continues northwards and that here a new Andes range starts near the coast, also in a north direction. Coast and range, therefore, enclose the same angle of 30° with the direction of the mantle-current as the first Andes section south of Arica, where we likewise found high negative anomalies in the gravity profiles. *)

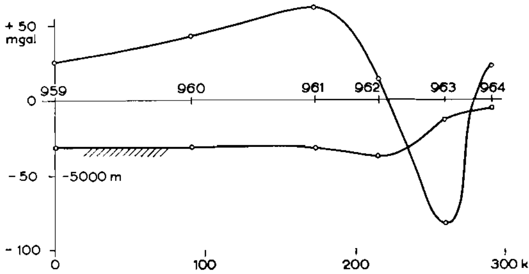

Figure 10. Gravity profile on the Westcoast of South America at 4°14'N (lat. of the coastal station); see map 2

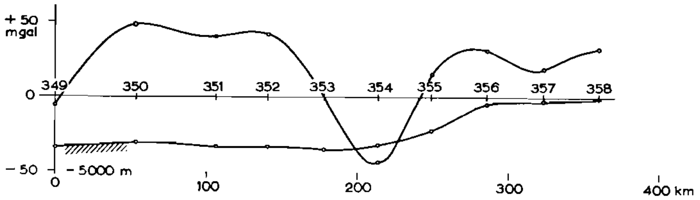

Figure 11. Gravity profile on the Westcoast of South America at 8°00'N (lat. of the coastal station); see map 1

Ewing's profile (Fig. 11) as well as the Walrus expedition profile, (Fig. 12) which are nearly coinciding, show small negative anomalies, viz. —44 mgal (station No. 354) and —23 mgal (station W1014) just outside the ESE coast of the peninsula of the republic of Panama. It may perhaps be attributed to the angle enclosed by this coast – which has an azimuth of about N65°E – and the mantle-current. This angle amounts to about 25° and might, therefore, bring about some slight effect of over-

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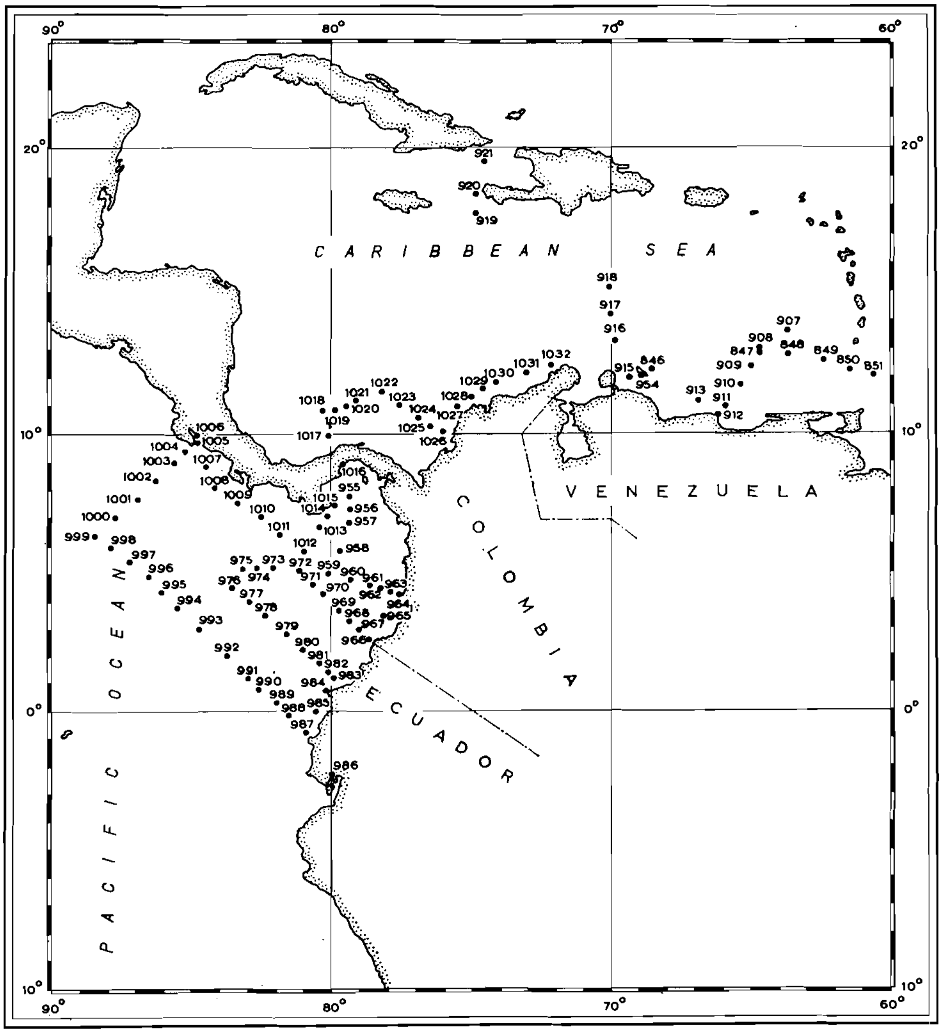
*) In Gravity Expeditions Vol. V, Publ. of the Netherl. Geodetic. Comm. Delft, 1960, the writer, in an attempt to an interpretation, mentioned the possibility, that a mantle-current towards the southeast which in California causes the crustal part east of the San Andreas fault to move to the southeast, could make itself felt also here, in the neighbourhood of the isthmus, and thus could bring about the high negative anomaly in this profile. Although it is possible, that this plays a part, the writer thinks that the explanation given here, is more likely.



Map 2

riding of the peninsular coast over the sea-floor. We need not go deep into this matter; the neighbouring stations show that this small effect is local.

A similar effect, though slightly larger, also in extent, is shown by Fig. 13 in which the stations No. 359 and No. 360 on the other side of the isthmus give anomalies of —50 mgal and —60 mgal respectively. They check well with the anomaly of

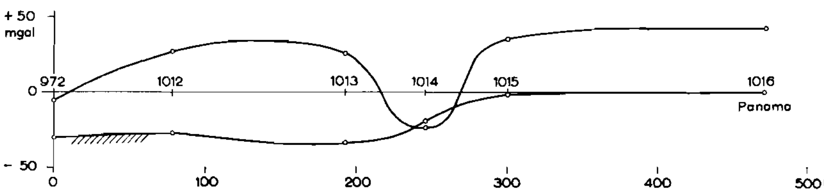


Figure 12. Gravity profile on the Westcoast of South America at 8°57′N (lat. of the coastal station); see map 2

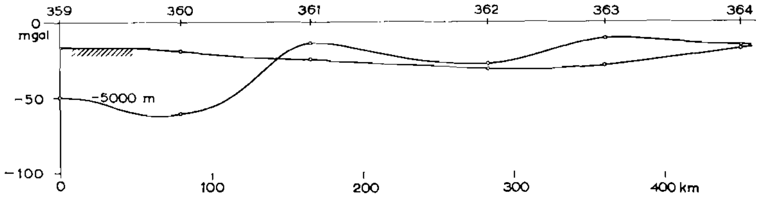
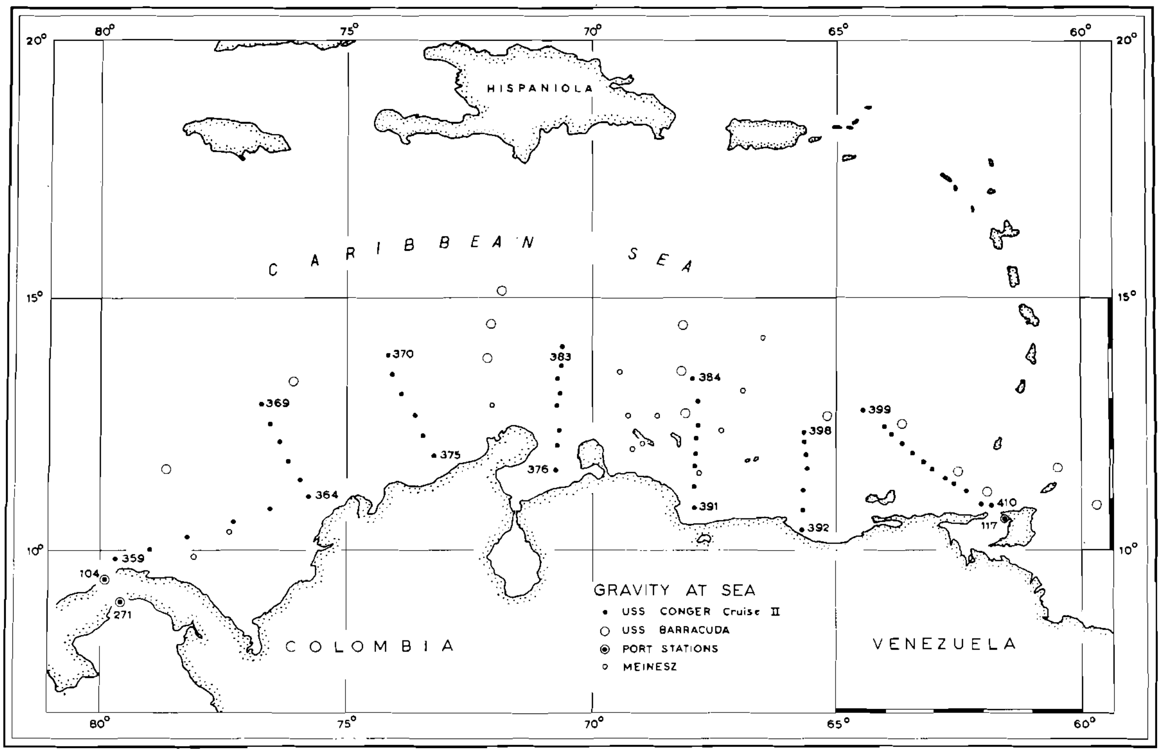


Figure 13. Gravity profile on the Northcoast of South America at 10°00′N (lat. of the coastal station); see map 3

—58 mgal shown by station W 1017 of Hr. Ms. Walrus expedition (see map 2) at about 40 km WNW of station No. 359. These stations are near the North coast of Panama and the mantle-current must here cause a still stronger overriding of the continental crust of the isthmus over the oceanic crust north of it. This interpretation seems to find some confirmation by the results found in station No. 361, which shows an anomaly of —14 mgal, while an old station to the SSE from N. 361 at a distance of about 60 km and, therefore, nearer to the isthmus coast shows an anomaly of —43 mgal.

The profile of Fig. 14, running from near Cartagena to the NNW, does not show large anomalies. A tendency near the coast towards negative values as shown by the stations No. 364 (—15 mgal) and No. 365 (—23 mgal) is confirmed by the stations W 1024, W 1025, W 1026 and W 1027 of Hr. Ms. Walrus expedition (see



Map 3

map 2) which gave −18, −13, −21 and −26 mgal in the same area. As the coast makes here a slight angle towards the east with the south-north direction it encloses a small angle with the supposed direction of the mantle-current and so we can understand some overriding of the continental crust over the sea-floor crust, which can explain this tendency.

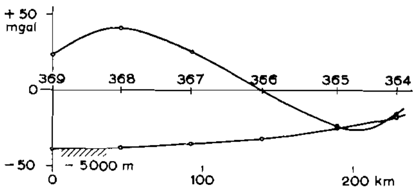


Figure 14. Gravity profile on the North-coast of South America at 75°45′W (long. of the coastal station); see map 3

The profiles of Figs. 15–19 all show large anomalies; they are situated in that part of the Caribbean area that is subject to strong crustal deformation. These profiles give some valuable information about further details of these disturbances. They do not bring any change in the view, that the deformations of the crust here are due to the same great subcrustal current hitherto discussed in this paper. Its azimuth here is N30°E to N35°E. The earlier knowledge about the belts of large negative anomalies in this area has been mainly provided by the expedition of U.S.S. Barracuda in 1938, on board of which the observations have been made by M. Ewing, H. H. Hess and A. J. Hoskinson; some observations had already been made by H. H. Hess, T. T. Brown and the writer during the expedition of U.S.S. 48 in 1932, by the writer during his expedition with Hr. Ms. K. 13 of the Royal Netherlands Navy in 1926 and by the Walrus expedition in 1957.

The main gravimetric features are two belts of large negative anomalies, one starting near Cape Maysi and running north of Haiti and Puerto Rico, outside the Antillean arc, over Barbados, towards Trinidad and eastern Venezuela; the other is offset to the NNE over about 300 km with regard to the end of the first belt and continues over and north of the island of Bonaire, north of the islands of Curaçao and Aruba and ends north of the mouth of the Magdalena river. For a long time the connection between the first belt up to Trinidad and the second belt near Bonaire was uncertain; it was usually supposed that, via a curved track, both belts were directly connected. Gradually, however, it was found that this was not true and that there existed an offset between the two belts. This was the first time an offset of such huge downbuckled crustal structures was found.

Besides the survey at sea, the Royal Dutch/Shell oil companies made an intensive and detailed gravimetric survey on land in Venezuela and Columbia. As the map of this survey shows, it did not indicate the existence of continuous belts of negative anomalies on land, but it showed several small patches of such anomalies.

The pattern of the first belt of strong negative anomalies at sea could satisfactorily be explained by assuming a uniaxial compressive stressfield in the crust, caused by the mantle-current as mentioned. This uniaxial stress was, therefore, assumed to have a direction with an azimuth of about S30°W–N30°E. The belt of strong negative anomalies east of Haiti up to Anguilla, as well as the similar belt between Anguilla and Barbados, make angles of 55° with the direction of the compressive stress, which is in harmony with Bylaard's theory of plastic deformation of a thin plate under compression (or under tension). Between Barbados and Tobago the negative anomalies are smaller and the direction of the belt makes an angle of about 25° with the stress; this agrees well with the supposition that here the relative movement of the crustal block inside the arc and that outside the arc is shear combined with overriding. In Trinidad we find again strong anomalies in a belt having an azimuth of N85°E, and this again checks well with the direction of plastic deformation under an angle of 55° with the compressive stress. So the whole belt can well be explained by the stress-field in the crust, as caused by the supposed mantle-current.

The pattern of the second belt of strong negative anomalies is somewhat more complicated. The western part up to the meridian of 70° western longitude encloses an angle of 55° with the direction of the subcrustal current, and so this again is in good harmony with the supposition of plastic downbuckling of the crust. At the western end of this part of the belt important new information is given by the profile of Fig. 15, which we shall presently discuss. East of this meridian the belt over some distance seems more or less to follow the coast of South America and further to the east it makes the impression of becoming patchy; this part also will be discussed when we examine the profiles of Figs. 17, 18 and 19.

We shall now undertake the discussion of the profiles of Figs. 15–19 and in doing so we shall also touch on the problem of the formation of the Sierra de Merida and of other mountain ranges which seem to be prolongations of the Andes.

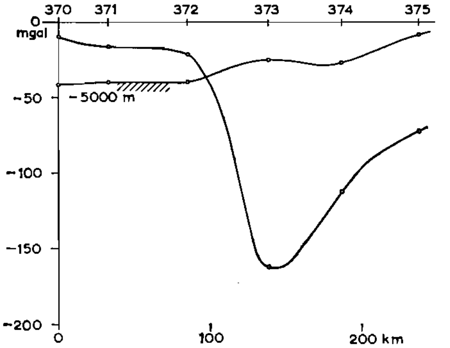


Figure 15. Gravity profile on the Northcoast of South America at 73°13′W (long. of the coastal station); see map 3

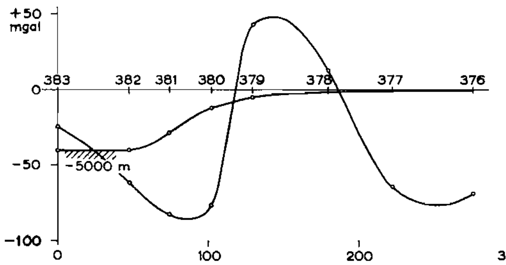


Figure 16. Gravity profile on the Northcoast of South America at 70°44′W (long. of the coastal station); see map 3

The profile of Fig. 15 is a valuable source of further information about the strong negative anomalies obtained o/b Hr. Ms. Walrus in a profile about parallel to the coast near the mouth of the Magdalena river. The stations W1028, W1029, W1030, W 1031 and W 1032 had provided the anomalies of −2, −82, −126, −40 and −46 mgal respectively. These stations had in fact revealed the western beginning of the above mentioned second belt of strong negative anomalies. This belt thus seems more or less to be the continuation of a belt of negative anomalies along the Magdalena river, which shows patches of strong anomalies, here and there even exceeding values of −100 mgal.

The profile of Fig. 15 gives a cross-section of this second belt at a distance of about 100 km to the NE of station No. W1030 (anomaly −126 mgal). This profile runs to the NNW from station No. 375 at a distance of about 50 km off the coast. Inland the gravity map of the oil companies at this point shows a small patch of anomalies exceeding −75 mgal. (i.e. more negative); it may be the direct prolongation of the results given by the profile. Starting from the SSE the profile comprises the stations 375, 374, 373, 372, 371 and 370 which provide the anomalies −72, −111, −162, −20, −16, and −9 mgal respectively. So we see that this profile shows exceptionally large negative anomalies and that the trend of the anomaly belt between this profile and the preceding one is about parallel to the mantle-current, but that eastwards from this profile it has an azimuth of N85°E, thus enclosing an angle of 55° with it as mentioned above. This southward twisted western end of this belt of negative anomalies may perhaps be understood by means of a hypothesis already previously made by the writer, that the great crustal block of the South American continent, which is dragged along by the mantle-current in a direction N30°E, is bounded by a great crustal faultplane (or faultzone) running from the isthmus between Colon and Panama in the same direction, i.e. towards Windward Passage or Haiti. To the northwest of this faultzone no great crustal deformation takes place, but to the southeast of it, we find the two belts of strong deformation caused by the movement of the South American block through the effect of the mantle-current. This hypothesis might explain that the second belt at its western end is twisted southwards.

Before leaving this part of the second belt, bounded by the meridian of 70° west, we shall briefly discuss the Sierra de Merida, which is the continuation of the most eastern chain of the Andes. Its azimuth is about N60°E. This mountain range has been studied by HOSPERS and VAN WYNEN *), who observed a gravity profile across it. Their conclusion was, that it was formed by the overriding of one great crustal block over the adjoining block. This overriding occurred along a faultplane parallel to the range and under an inclination of about 30°.

According to their interpretation, this faultplane originated under the effect of the crustal compression, caused by a mantle-current which drags a great part of the North American continent towards the southeast and thus brings about the large relative displacement along the San Andreas fault and parallel faults close to it.

The writer agrees entirely with the conclusions of HOSPERS and VAN WYNEN about the origin of the range by the overriding along a great faultplane of the southeastern crustal block over the northwestern block. Besides the strong argument provided by the asymmetrical gravimetric profile over the range, it is also likely because of the huge escarpment shown by the surface of the cretaceous limestone as published by these authors in Fig. VI-6 on page 48 of their paper. This figure likewise shows clearly the direction of the strike of the faultplane.

For at least two reasons, however, the writer feels inclined to differ from these authors as to the origin of the forces and the mechanism in the crust bringing about this overriding. Basing themselves on the work of GUNN **), their view, that a compressional stress-field in the crust in a direction at right angles to the strike of

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*) HOSPERS, J. and VAN WYNEN, J. C., The Gravity Field of the Venezuelan Andes and adjacent basins, Verh. Kon. Ned. Akad. v. Wetensch. 1st reeks, Dl. XXIII, No. 1; Noord-Holl. Uitg. Mij. Amsterdam, 1959.

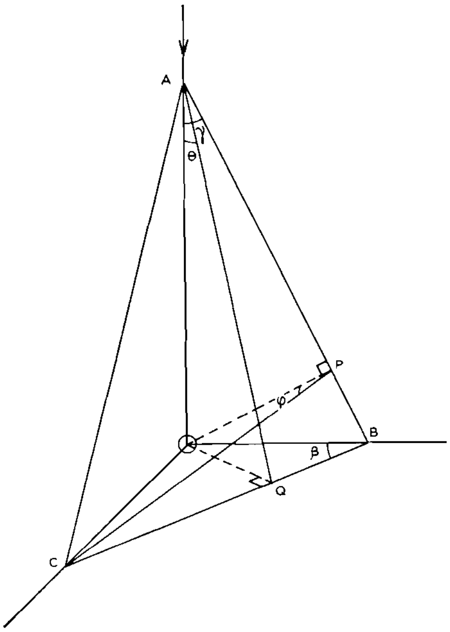
**) GUNN, R., Quantitative aspects of juxtaposed ocean deeps, mountain chains and volcanic ranges; Geophysics, Vol. XII, 1947, pp. 238–255.

the faultplane can cause this plane, seems difficult to reconcile with the view that elsewhere such a stress-field brings about a geosyncline. A still more serious objection is founded on the fact that in the whole area of South America and the Caribbean the crustal stress has a direction given by the azimuth N30°E, which differs entirely from the direction at right angles to the Sierra de Merida.

As, however, the strike of the Sierra de Merida has an azimuth of N60°E, it encloses an angle of 30° with the last mentioned direction, which is also the direction of the mantle-current below the crust, it is obvious that the faultplane through this Sierra can have originated by the drag on the crust exerted by that current and that at the same time this drag can have brought about an overriding of the southeastern block over the northwestern one. We thus find that the formation of this mountain range is just a part of the many effects of this mantle-current, that we have already considered. So we do not need any further explanation of it.

There is still one point in our supposition which needs investigation. Overriding of the southeast side of the crust over the northwest side requires a tilted faultplane and this implies the question whether the angle enclosed between this tilted plane and the horizontal direction of the compressional stress in the crust is inside the range of 25°–30° which the theory of shear of Anderson, Hubbert, Hafner and others demands. If the angle enclosed between the stress and the horizontal strike of the faultplane is 30°, as it here is the case, the angle mentioned is less.

In similar problems, this point, as far as the writer knows, has always been neglected. It is worth while to look into it. It concerns a problem of stereometry, which is illustrated in the figure hereunder.



In this figure AOB represents the plane of the crust, i.e. the horizontal plane, and OA the direction of the compressional stress. ABC represents the faultplane through the crust and so γ is the strike in the horizontal plane of the faultplane with regard to the stress direction. OP and CP are perpendicular to AB and so the angle φ is the angle of elevation of the faultplane with regard to the horizontal plane. AQ and OQ are perpendicular to BC and so angle θ is the angle we want to derive between the direction of stress OA and the faultplane ABC. We introduce the angle β between CB and OB. If we assume that OA is the unit of length, we have $OB = \tan \gamma$, $OP = \sin \gamma$, $OC = OP \tan \varphi = \sin \gamma \tan \varphi$ and $OQ = \tan \theta$. This leads at once to the formulae

$$\tan \beta = \cos \gamma \tan \varphi \quad . \; . \; . \; . \quad (1)$$

$$\tan \theta = \tan \gamma \sin \beta \quad . \; . \; . \; . \quad (2)$$

and by means of these formulae we can determine θ for different values of the angle of elevation φ of the faultplane. For a value of $\gamma = 30°$ we find

φ	90°	75°	60°	45°	30°	15°	0°
θ	30°	28°48′	25°39′	20°42′	14°28′	7°26′	0°

A fair approximation of these values, at least for values of φ, which are not too small, which anyhow have no significance, is given by the formula:

$$\theta = \gamma\ (1-1.56\ 10^{-4}\ \varphi_c^2)\ \dots\dots\dots\dots\dots\dots \quad (3)$$

in which φ_c is the complement of φ, in degrees, i.e. the angle of hade of the faultplane. From our figures, as well as from this formula, we derive that for $\gamma = 30°$ the value of φ_c has to be smaller than 32.7 in order to keep θ above 25°. An angle of hade up to this value is certainly large enough to understand that the shear movement implies overriding, and it is also large enough for explaining the gravity profiles over the Sierra de Merida, published by Hospers and Van Wynen on page 73 of their paper.

Taking up the study of the crustal deformations and the gravity anomalies in the area of the second belt east of the meridian of 70°W, we may first examine the continuation in this area of the most eastern chain of the Andes. It here forms the Sierra de la Costa and, further east, the Sierra de Cumana. Both have an azimuth of N85°E and so they enclose an angle of 55° with the direction of the mantle-current which we suppose to be present. This is in good harmony with the fact that these chains are characterized by strong folding, and so here again our hypothesis about the direction of the mantle-current is confirmed. Our views are likewise confirmed by the presence of the strong negative gravity anomalies in the Cumana area, which we have already mentioned as forming the end of the first belt of strong negative anomalies. The writer does not dispose of the gravity field below the Sierra de la Costa.

After this long digression we shall again take up the study of the gravity profiles. The profile of Fig. 16 has a North-South direction and is situated over the Gulf of Maracaibo. It shows two strongly negative anomalies of −82 mgal and −78 mgal over the continental slope. They form part of our second belt which here changes its direction; further east it has an azimuth of about N105°E and more or less follows the shelf edges of the islands Aruba, Curaçao and Bonaire; it is situated somewhat to the north of it. Just east of the latter island, where we dispose of the profile of

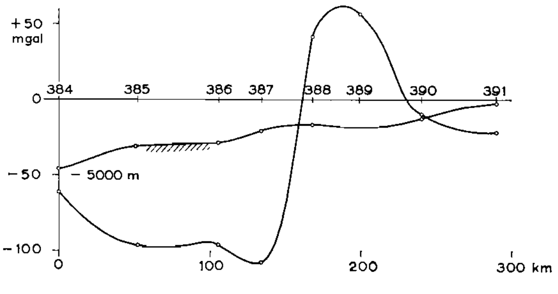


Figure 17. Gravity profile on the Northcoast of South America at 67°54′W (long. of the coastal station); see map 3

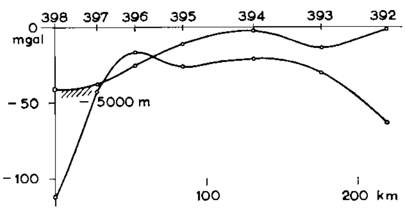


Figure 18. Gravity profile on the Northcoast of South America at 65°40′W (long. of the coastal station); see map 3

Fig. 17, the belt gets broader on the south side. In this profile we find the strongly negative anomalies of —96, —95 and —108 mgal, which together seem to suggest a second belt welded to the first. This probably is connected with the fact that north of Bonaire, as shown by the bathymetric map, we find the western end of the Los Roques trench, which is separated from the Caribbean by the Curaçao Ridge. A slight indication of a gravimetric effect connected with this trench is also found in the profile of Fig. 18, which in station No. 398 shows a strong anomaly in the main belt of —111 mgal, but also in station No. 395 an anomaly of —26 mgal which is slightly smaller than the anomalies of —17 mgal and —21 mgal to the north and to the south of this station.

Going back to the profile of Fig. 16, we see that in the Gulf of Maracaibo two negative anomalies occur of —64 mgal and —69 mgal respectively. Without further gravity observations it is difficult to decide whether these anomalies form part of still another belt of negative anomalies, which, though weaker than the main belt, can be followed to the east towards the stations No. 391 (anomaly —21 mgal at the southern end of the profile of Fig. 17) and No. 392 (anomaly —63 mgal at the southern end of the profile of Fig. 18).

We see that this whole area, in which we dispose of the profiles of Figs. 16, 17 and 18, shows a clear belt of negative anomalies in the north, which in fact is our "second belt", and shows weaker indications of other negative belts; they may, however, also be regarded as more or less isolated patches of negative anomalies.

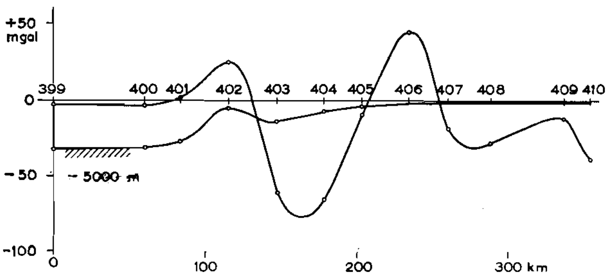


Figure 19. Gravity profile on the Northcoast of South America at 61°50'W (long. of the coastal station); see map 3

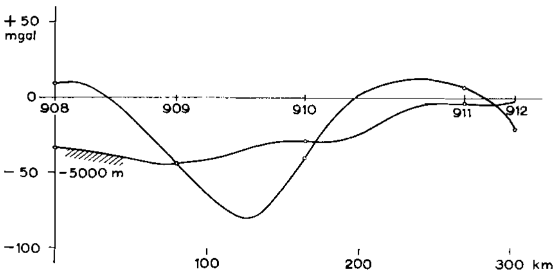


Figure 20. Gravity profile on the North-coast of South America at 66°00'W (long. of the coastal station); see map 2

In the profile of Fig. 19 we find negative values in the stations No. 403 and No. 404, which show anomalies of —61 mgal and —65 mgal respectively. They may probably be considered to represent the continuation of the main "second belt", which further to the east disappears. This supposition of continuation of this belt is in harmony with a gravity profile between the profiles of the Figs. 18 and 19, which has been observed by Dr. Dorrestein during a gravity expedition on board of Hr. Ms. submarine "Tijgerhaai" in 1951; this expedition was made under the auspices of the Netherlands Geodetic Commission, and the results have been published in "Gravity Expeditions", Vol. V, Delft 1960. This profile is here given in Fig. 20, it runs from Cape Codera to the NNE, crosses the profile of Fig. 18 near station No. 394, and comprises the stations T908–T912.

Near our belt we find the stations No. T909 and No. T910 with the anomalies of −46 mgal and −40 mgal respectively on both sides of our belt. This localizes our belt at the exact spot between the profiles of Fig. 18 and Fig. 19, where we might expect it, when we assume that the stations No. 403 and No. 404 of the profile of Fig. 19 really represent the continuation of our belt. It is a pity that the distance of about 80 km between the stations No. T909 and No. T910 is too large for estimating the maximum negative anomaly in the centre of the belt. The value of about −80 mgal given in the profile of Fig. 20 is no more than a possible value.

We are now in a position to discuss the relation of the second belt of negative anomalies to the first belt from Cape Maysi to Cumana. The profiles of Figs. 15–19 have considerably enlarged our knowledge of this second belt, which formerly was incomplete. Realizing that the belts north of Puerto Rico, outside the Antilles from near Anguilla till Martinique, in Cumana and north of Venezuela can all be interpreted as belts of crustal downbuckling and, therefore, as belts in which the crust was shortened over several tens of kilometers in a sense at right angles to the belt, we have to conclude that the second belt is simply the continuation of the first, but that the downbuckled belt is offset from the western end of Cumana towards the eastern end of the second belt. This offset occurs at an azimuth of N30°E, i.e. in the direction of the mantle-current, which checks with our view. It would of course mean that along this zone of offset the northwestern crustal block moves with regard to the southeastern block. In a recent paper *) the writer pointed out, that in several instances relative movements of crustal blocks appear to occur along a faultzone, that must be supposed to be parallel to the mantle-current causing the relative movement. We can understand that in this case no overriding of one block over the other takes place, and that no earthquakes occur, which could reveal the movement. One of these instances the writer mentioned is the case we here meet. He also discussed a case of much smaller dimensions which GUTENBERG mentions on page 207 of the 2nd edition of "Internal Constitution of the Earth", where he points out how in the Buena Vista Oilfield, in Kern County in California, two crustal blocks move with regard to each other with a velocity of about 3 cm/year and without earthquakes accompanying the phenomenon. Bending of pipelines reveals this gradual crustal deformation and from the shearing off at various depths of the casings of wells, GUTENBERG concluded that the movement occurs along a faultplane dipping under an angle of approximately 25°. This remarkable phenomenon leads us to suppose that perhaps the relative movement of greater crustal blocks of the type we are here dealing with, also takes place along a faultplane through the crust.

In the West Indies there is probably another phenomenon of this kind on a still greater scale. As it has already briefly been mentioned this seems to take place along a crustal faultplane that separates the part of the Caribbean area northwest of it, which remains undeformed, from the part southeast of it, where we find the two belts of negative anomalies in which the crustal deformation is centred. The zone, in which this plane must be situated, is no doubt bounded on the southeast side by

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*) VENING MEINESZ, F. A., Pseudo-viscous shearzones in the earth's crust, three possible systems of mutual reaction of large crustal blocks; Proc. Kon. Ned. Akad. v. Wetensch., Ser. B, 65, No. 4, 1962, pp. 327–333.

a line starting with an azimuth of N30°E from Punta Brava and continuing along the 1500 fathoms contour of the Caribbean, along the northwest coast of Colombia, and along the Beata Ridge, towards Silver Bank Passage between Silver Bank and Mouchoir Bank; and bounded on the northwest side by a line with the same azimuth over Mosquito Gulf (to the west of Cristobal) towards Windward Passage and Caicos Passage, between Mariguana Island and Caicos Island. The writer should not like to express an opinion where in this zone the fault is situated, whether there are perhaps more than one faultplane, or whether the whole zone is subject to pseudo-flow. In the same way as the former phenomenon, it is not accompanied by earthquakes.

We have still to examine the problem why the second belt of strong negative anomalies, east of the meridian of 70° western longitude, encloses a different angle with the mantle-current from the two normal angles of 55° or 25°–30°. Only between 65°40′ and 66°40′ western longitude the azimuth is about N85°E and so the angle is about 55°. The parts of the belt to the west and to the east of this stretch have an azimuth of about N105°E and so here the angle enclosed with the mantle-current is about 75°.

We may probably attribute this abnormal direction to pressure exerted by the continental crust of South America on the crust below the Caribbean. The Los Roques trench, the Bonaire trench and the Cariaco trench are probably likewise due to this pressure. Although the pressure exerted by the continent must in general be expected to have a direction identical to that of the mantle-current, i.e. with an azimuth of N30°E, we can understand that the deformation in the adjoining Caribbean crust is influenced by the shape of the coast. It is difficult to conjecture how much this shape has been affected in the course of time by the dextral shear along the faultplanes of the Andes chains, which must have tended to push northwards the western part of the northcoast of South America, and thus must have changed its general direction.

None of the three trenches mentioned are deep. They seem all to be accompanied by negative anomalies, but apparently these belts of anomalies are slightly shifted to the south with regard to the trenches. As far as this is the case for the Los Roques trench, to the north of the islands of Curaçao, Bonaire, the Aves Islands and more small islands to the east, this may be due to the fact that the first two islands, and probably also the others, are for a great part formed by diabase eruptions along a great faultplane in the direction of the island ridge, and that, therefore, this island ridge infringes on the southern edge of the Los Roques trench.

We thus can understand that in the profile of Fig. 17 station No. 387, to the east of Bonaire, shows an anomaly of −108 mgal, which, therefore, is situated south of the Los Roques trench. It may perhaps be supposed that the original southern edge of the trench was formed by this faultplane.

II. THE PUERTO RICO TRENCH; TWO TYPES OF DEEP OCEAN TRENCHES

During recent years much new geophysical research was carried out in the area of the Puerto Rico trench, especially by the scientists of the Lamont Geological Observatory of the Columbia University, by M. and J. Ewing, M. Talwani, G. H. Sutton, J. L. Worzel and others. In the October number of "Geophysical Research" of 1959 a paper by Talwani, Sutton and Worzel appeared under the title: "A Crustal Section across the Puerto Rico Trench", in the September number of 1962 one by Elizabeth T. Bunce and Davis A. Fahlquist about "Geophysical Investigation of the Puerto Rico Trench and Outer Ridge", and in the November number of 1962 one by John and Maurice Ewing under the title: "Reflection Profiling in and around the Puerto Rico Trench". The valuable data obtained and the important papers mentioned allow a check of the geophysical conclusions the writer long ago came to, and in fact allow to give these conclusions a firmer base. They lead to a deeper understanding of the phenomena.

As the writer has set forth in "Plastic Buckling of the Earth's Crust: The Origin of Geosynclines" *) and in chapters 10A and 10C, especially section 10C–5, of "The Earth and its Gravity Field" **), the belts of strong negative gravity anomalies, which we find in the island-arc areas, and in which deep trenches occur, are belts of crustal downbuckling, where because of this process the isostatic equilibrium of the crust is strongly disturbed. Over the Puerto Rico trench we likewise find such a belt of strong negative anomalies, which in the axis, after isostatic reduction, exceeds values of −150 mgal. It continues further east around the smaller Antilles. North of Puerto Rico the axis of the belt is located about 50 km south of the deepest part of the trench, but as Figs. 2 and 3 show, the crustal cross-sections of Talwani, Sutton and Worzel, and of Bunce and Fahlquist, which have been derived from the results of seismic shooting and gravity observations, indicate that this is caused by a superficial crustal layer of sediments; the lower crustal layers show the position of the axis of the downwarp to be about coinciding with that of the anomaly belt. Such a displacement of the trench axis is also present in the Indonesian archipelago, viz. in the Java trench south of Java ***), where it must be due to the same cause; the sediments coming from the Java side do not fill the entire downwarp, and thus the axis of the trench at the crust's surface is shifted towards the ocean side.

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*) Geol. Soc. Am. Special Paper 62, 1955, pp. 319–330 ("The Crust of the Earth").

**) Heiskanen, W. A. and Vening Meinesz, F. A.; The Earth and its Gravity Field, McGraw-Hill, 1958.

***) Vening Meinesz, F. A., Indonesian Archipelago: a Geophysical Study; Bull. Geol. Soc. Am. Vol. 65, 1954, p. 147.

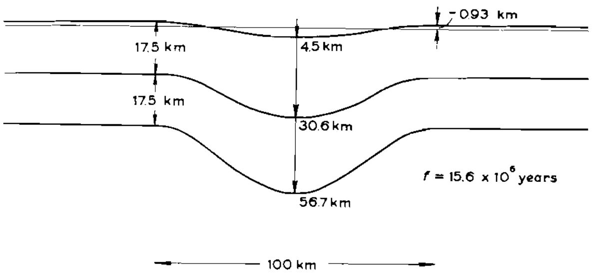

Figure 1. Plastic crustal downbuckling of the rigid crust on true vertical scale; upper and lower crustal boundaries and axis plane (taken from „The Earth and its Gravity Field" by W. A. Heiskanen and F. A. Vening Meinesz, McGraw-Hill, New York, Toronto, London, 1958, Fig. 10A-11, p. 347).

According to the physical process of crustal downbuckling, as set forth in the papers mentioned, the crust undergoes a plastic thickening brought about by strong horizontal compression. This compression, causing crustal thickening, also leads to the downbuckling of the crust. The combination of both effects is shown by Fig. 1, taken from page 347 of "The Earth and its Gravity Field", which was theoretically derived on the basis of the supposition of a crust floating on a denser mantle and horizontally compressed by a stress above its strength, causing, therefore, plastic deformation.

Before continuing our discussion, the writer may mention his hypothesis, that the strong horizontal compression of the crust is brought about by convection-currents in the mantle, which exert drag forces on the crust. This hypothesis rests on so many arguments that the writer considers it as close to certain. For these arguments he may refer to a paper in the Proceedings of the Amsterdam Academy of Sciences of 1961, "Convection-currents in the Mantle of the Earth", pp. 501–511. He dealt with the pattern of these currents in the present period in a paper, "Pattern of Convection-currents in the Earths' Mantle", Proc. Amsterdam Academy of Sciences, 1962 pp. 131–143. The mantle-current to which we may attribute the origin of the Puerto Rico Trench may be supposed to exert a drag on the crust in an azimuth of about N30°E.

Taking up again our main subject, we may examine how far the crustal profiles, given by Talwani, Sutton and Worzel, and by Bunce and Fahlquist and represented by Figs. 2 and 3, check with the crustal deformation here supposed and represented by Fig. 1. We see that these observers do not assume a cross-section of the crust which is in harmony with the principle of crustal downbuckling, but we likewise see that they conclude to a thickening of the crustal matter in the trench area. From Fig. 1 we derive a thickening ratio of 1.62, from Figs. 2 and 3 one of about 1.60. These figures agree well with each other. For the density of the deepest crustal layer in the trough, Bunce and Fahlquist find a value of 3.05, which is only a little more than that of basalt – which is usually considered to be the chief constituent of the lower crustal layer – and at least part of the small difference may be attributed to the greater hydrostatic pressure at that depth and to the strong horizontal compression causing the crustal downbuckling. Talwani, Sutton and Worzel give a figure of 3.0 which also checks with the supposition of basalt.

So we find that the results of both groups are in good harmony with the hypothesis of crustal thickening and downbuckling and as it is difficult to find another acceptable explanation for the great isostatic gravity anomalies in the Puerto Rico trench, the writer thinks that this hypothesis as well as that of a mantle convection-current

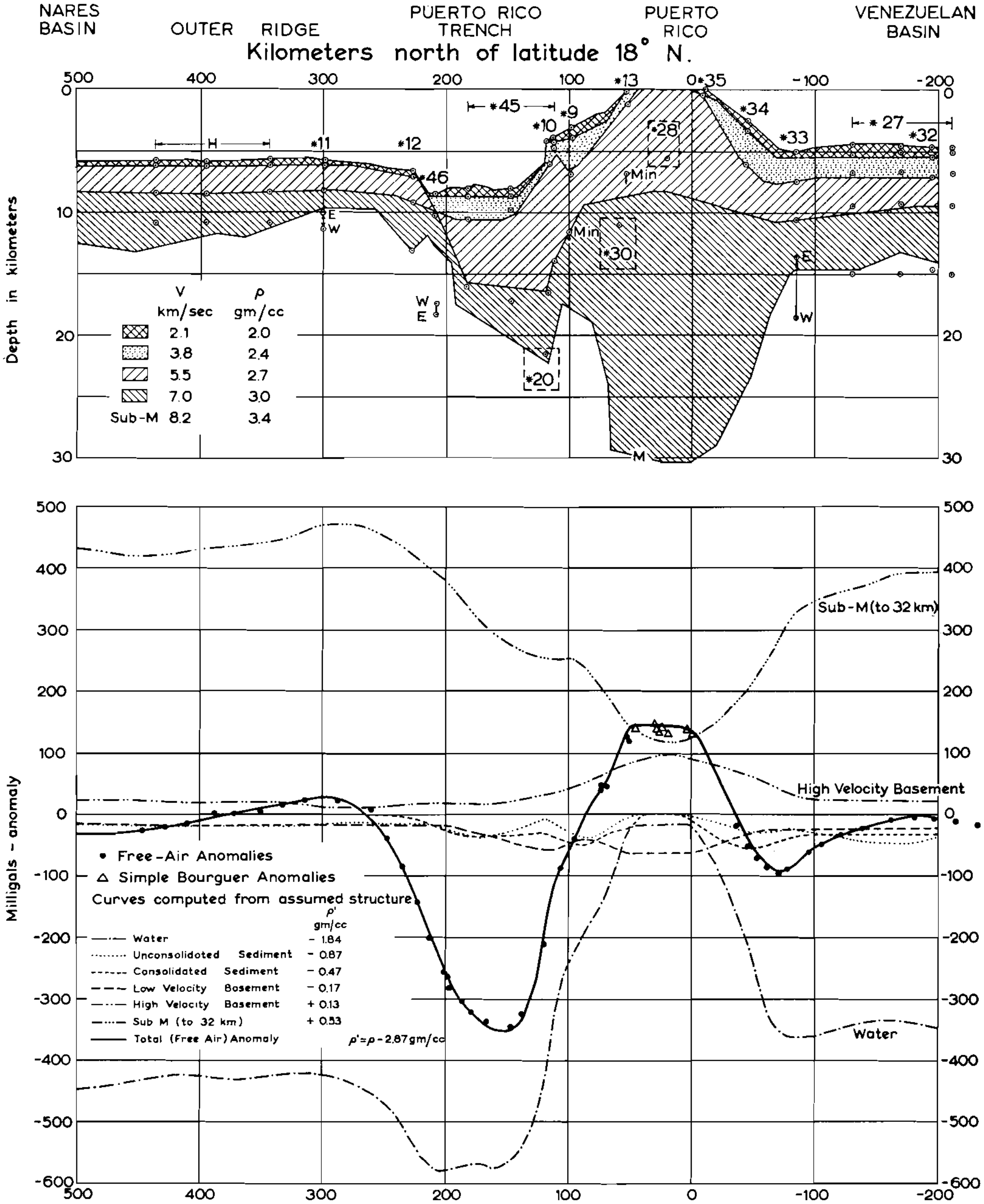

Figure 2. *Upper* – Computed crustal section. Crustal layering is from seismic data; *M* is from gravity data; points are seismic interfaces.
Lower – Computed attraction of layers to 32 km depth using reduced densities ϱ'. Solid curve is total attraction (computed free-air anomaly) which is compared with observed anomalies.
(Taken from: "A Crustal Section across the Puerto Rico Trench" by M. TALWANI, H. G. SUTTON and J. L. WORZEL. J. Geophys. Res., 64, 10, 1959, Fig. 3, p. 1550.)

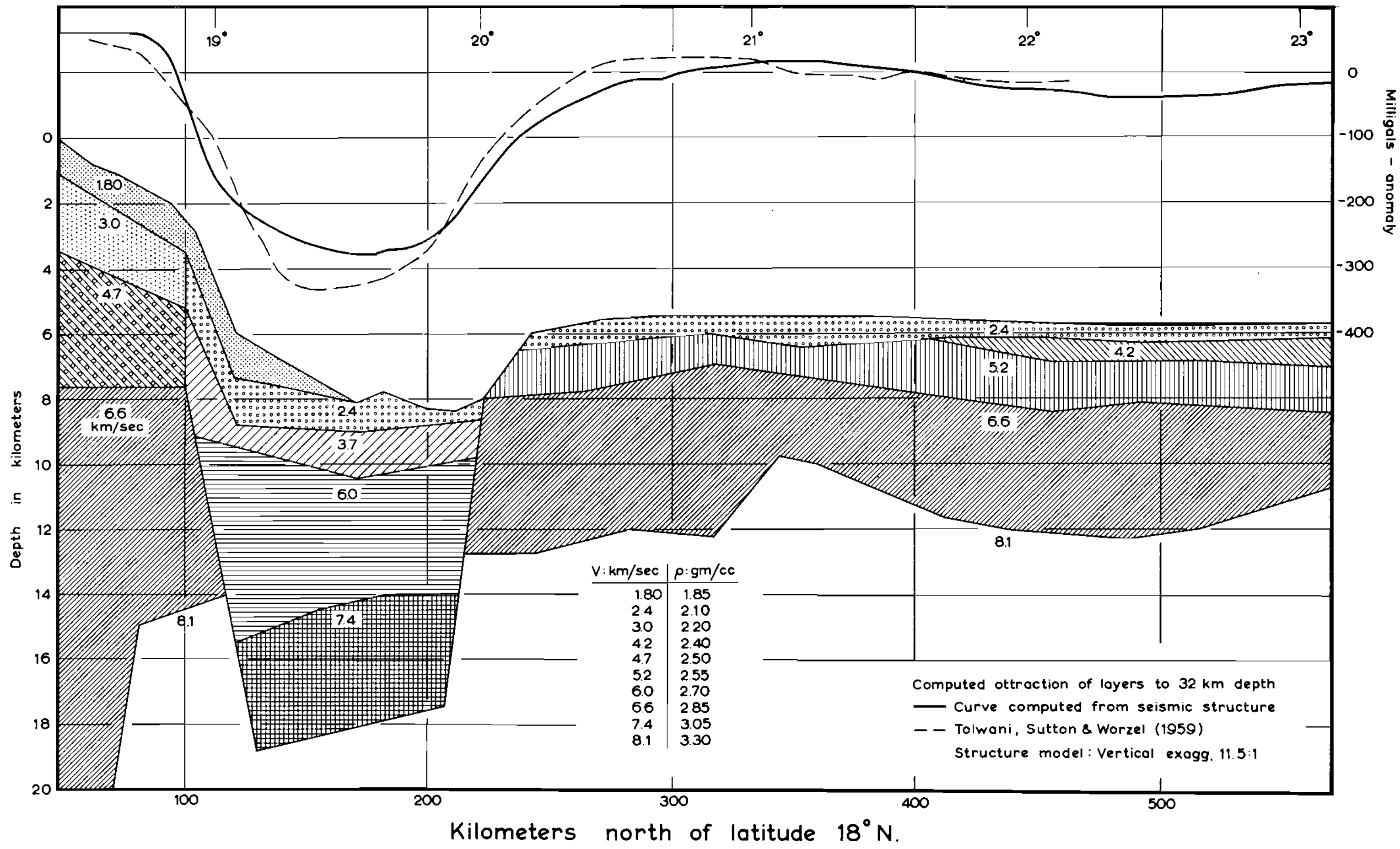

Figure 3. *Upper* – Comparison of computed free-air anomaly (solid line) and measured anomaly (dashed line).
Lower – Crustal layer model and assigned densities for computed total attraction (free-air anomaly).
(Taken from "Geophysical Investigation of the Puerto Rico Trench and Outer Ridge" by ELIZABETH T. BUNCE and DAVIS A. FALQUIST, J. Geophys. Res., 67, 10, 1962, Fig. 3, p. 3962.)

causing the horizontal compression may be considered as well established, it, moreover, explains the gravity anomalies in the whole Caribbean arc and also, as Fig. 1 shows, the presence of the outer ridge. So we may state that, according to the results published by Talwani, Sutton and Worzel and by Bunce and Fahlquist, the recent seismological observations confirm the hypothesis of crustal thickening and downbuckling in this part of the Caribbean arc. The supposition made with regard to the presence of a mantle convection-current in the direction as mentioned (azimuth N30°E) has thereby found a new support.

We shall now examine the results found by Maurice and John Ewing for the topographic cross-section of the Puerto Rico trench to the north of that island.

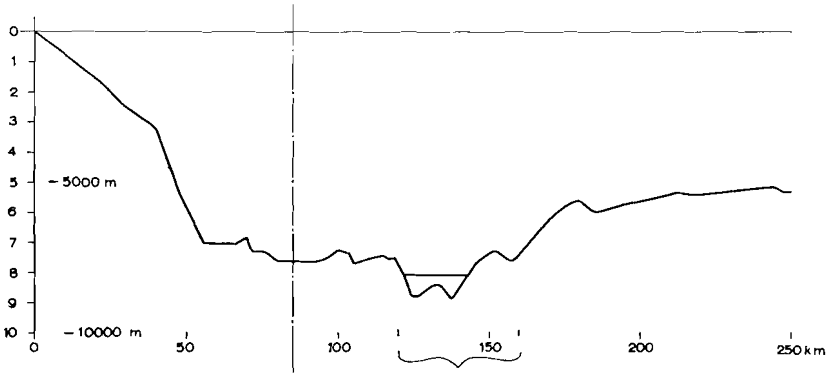

Figure 4. Reproduction of central part of Fig. 2 of "Reflection Profiling in and around the Puerto Rico Trench" by John Ewing and Maurice Ewing (J. Geophys. Res., 67, 12, 1962, p. 4731); the vertical exaggeration was reduced from 50 : 1 to 10 : 1.

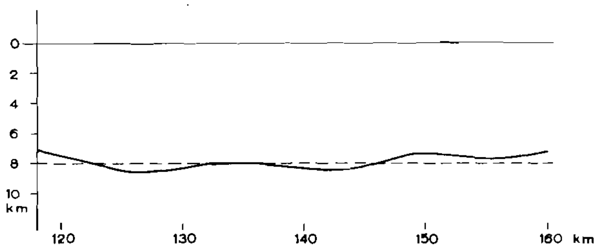

Figure 5. Central part of Fig. 4 on true vertical scale.

Fig. 4 gives a copy of their results as published in the November number of Geophysical Research of 1962, p. 4731, but on a vertical exaggeration of only 1 : 10; Fig. 5 represents the central part of the trench on true vertical scale.

These two figures show a fairly locally irregular topography. It appears to the writer that we may derive from these results a rather interesting conclusion. The theory of plastic downbuckling of the crust in the belt, indicated by the strong negative gravity anomalies, assumes a pseudo-viscous crustal thickening and downbending of the crust. If this supposition represented the complete truth, the topography of the crustal surface would show a regular curve throughout the whole area of the trench and the adjoining outer ridge. The fact that the detailed research of MAURICE and JOHN EWING revealed a quite irregular surface, points to a different behaviour of the surface layer of the crust. We can well understand this result. The temperature and the hydrostatic pressure are so much less than in deeper crustal layers, that we can understand a different behaviour with regard to the strong horizontal compression to which the crust here is subject. The elastic limit, which must be exceeded before pseudo-viscous reactions are possible, is here much higher and because of the smaller pressure, the behaviour must have a more brittle character. This can explain the formation of shearplanes and complicated deformation phenomena. Besides, as we have already mentioned, the area, up to a certain distance from Puerto Rico, is subject to sedimentation, which further complicates matters. In this paper we shall not further study these problems.

The writer may draw attention to the fact, that probably there are two ways in which deep trenches can originate. In the first place they may come into being by horizontal compression in the crust, which leads to crustal downbuckling. The Puerto Rico and Java trenches are instances of this type. In general this phenomenon is likely to be accompanied by shear-stresses in the length-direction of the trench but these stresses do not play a primary part in the trench-formation. They are probably the cause of volcanoes in the inner arc, but for this phenomenon the writer may refer to other papers, e.g. to that mentioned in note *** on page 23.

In the second place deep trenches may originate by horizontal shear along a tilted faultplane through the crust, accompanied by the overriding of one crustal block over the other. Instances of such trenches are probably found in the Philippine Trench the Japan Trench, and probably most other trenches in the island-arc areas east of Asia; also the trenches bordering on the westcoast of South America. It is interesting to see that for the Philippine Trench the strong isostatic gravity anomalies nearly vanish if we apply regional isostatic reduction *). The writer is not sure whether this would be true for all the other instances of this types of deep trenches. He can on the other hand affirm that this is not true for the Java trench *); the belt of strong negative gravity anomalies along this trench – which, as mentioned, is somewhat shifted with regard to the trench – remains strongly negative if regional isostatic reduction is applied. So it seems likely, that this represents indeed a systematic difference between both types of deep trenches.

Probably we can explain this difference by realizing that in the case of the Java and Puerto Rico trench type the crust may be supposed to have downbuckled, and that, therefore, a fairly local root of light crustal material is present below the crust, and that in the case of the trenches caused by overriding, a broader and shallower root is present, tapering off to one side. We can understand that in the latter case regional isostatic reduction, which is based on the supposition of similar roots of light crustal material, caused by crustal bending, may annul the anomalies.

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*) See: Gravity Expeditions at Sea, Vol. IV, Publication of the Netherlands Geodetic Commission, Delft, 1948.