Geophysics. — *Topography and Gravity in the North Atlantic Ocean.* By F. A. VENING MEINESZ.

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For the investigation of the Earth's crust under the oceans our data are scanty; we have only three sources of information. In the first place we can now obtain a detailed knowledge of the topography of the sea-bottom thanks to the new method of sonic sounding which so much reduces the trouble of determining the sea-depth. In the second place we have the data given by dredging, eventually made more valuable by shooting tubes over a few meters in the sub-oceanic soil. Thirdly we may obtain gravimetric results. It is true that we can also make a magnetic survey of the oceans as it has e.g. been done by the famous cruises of the ship „Carnegie" of the CARNEGIE Institution of Washington, but these results, though of high importance for the study of terrestrial magnetism, do not in general give much clear information about the crust and so we shall not further mention them here. Besides we of course also dispose of the geological evidence obtained on the oceanic islands and near to the coasts.

In this paper we shall give a provisional study especially of the submarine topography and the gravity results over part of the North Atlantic, i.e. over the Azores Archipelago and between the Azores and Europe. As the chart shows we dispose here of a fairly large number of gravity observations which, as it is well-known, the writer has been able to make on board of submarines of the Royal Dutch Navy; he feels a great debt of gratitude for the many opportunities given to him. He likewise feels indebted to the Netherlands Geodetic Commission on whose behalf the expeditions have been organized and which has also defrayed the expenses for the great amount of computational work needed to obtain the results published here.

The area is also well covered with soundings. The accompanying map showing the contour lines is a copy of a larger one made by Mr. BLOEM of the Hydrographic Service in the Hague for the report of the Netherlands Geodetic Commission about the gravity results obtained at sea [1]). It has been derived from the chart of the North Atlantic of the "Carte Bathymétrique des Océans", 3rd edition, issued by the International Hydrographic Bureau in Monaco in 1935, supplemented by the charts of the Azores and of the Altair area published by A. DEFANT and G. WÜST [2]).

Nevertheless, although the soundings and the gravity data are numerous compared with other oceanic areas, much more will be needed before a detailed study of this area can be made. Still it is worth while to examine the data now available; we shall see that we can already draw some conclusions and make some surmises.

Beginning by the topography we see that the map clearly shows a linear arrangement of most of the features. This is especially clear in the Azores where it has already been often remarked that in the topography two directions are predominant, one from WNW to ESE, i.e. under an azimuth of about 65° west, and the second from NE to SW, i.e. under an azimuth of about 45° east. Nearly all the islands and the submarine elevations have their length-axis in the first sense except the western group of islands of Flores and Corvo where the ridge follows the main direction of the Mid Atlantic Rise; they form in fact part of this rise, which here follows more or less the second direction. The middle

[1]) F. A. VENING MEINESZ, Gravity Expeditions at Sea, Vol. IV, to be issued in this year or the next.

[2]) A. DEFANT und BJ. HELLAND-HANSEN, Bericht über die ozeanographischen Untersuchungen im zentralen und östlichen Teil des Nordatlantischen Ozeans; A. DEFANT, Die Altair Kuppe; G. WÜST, Das submarine Relief bei den Azoren, Abh. Preuss. Akad. d. W. 1939, Phys. Math. Kl, 5.

group of islands of Fayal, Pico, São Jorge, Graciosa and Terceira together with the Princess Alice Bank in its general grouping also shows the second direction and this is likewise more or less true for the eastern group of São Miguel, Santa Maria and the bank to the south of it.

As far as the writer knows it has been less generally realized that these two directions are not only valid in the Azores but that we can probably also trace them in the whole area of the map east of this archipelago, although here and there slightly changed in direction. We find the second direction e.g. in a long ridge to the NE of the Azores, in a ridge to the NE of Madeira running towards the Seine Bank, in a ridge to the SW of the Josephine Bank and in a ridge connecting the Gorringe Bank with the Portuguese coast. The first direction shows itself e.g. in the ridge connecting the Cruiser Bank with the Mid Atlantic rise, in the ridge running WNW wards from a bank at about 43° N and 21° W towards this rise, in the ridge connecting the Gorringe Bank with the Josephine Bank, in a ridge to the NW of Cape Finisterre and perhaps in a ridge connecting the submarine promontory at about 43° N and 12° W with the Spanish mainland. It gives the impression that in this last area both directions are turned slightly anti-clockwise.

This linear arrangement of the topographic features in the Azores and probably also in the area east of them seems to point to block-faulting and not to folding and overthrusting; these last phenomena usually occur in curved belts while the first imply a system of more or less straight lines. The shearing is nearly everywhere accompanied by volcanism along the fault-lines; the islands show numerous instances of this as e.g. the island of São Jorge which consist of a long row of eruption points. The volcanoes often also occur in the points of intersection of the two directions as e.g. shown by the three groups of the Azores and by Madeira.

The gravity results are in good harmony with our tentative conclusion that no folding has occurred in our area. Although the seismicity of a great part of it indicates movements that are still going on, there is no evidence of any belts of strong negative anomalies as have been found in the East and West Indies and in other areas where young folding orogeny has been taking place and where these belts have been interpreted as an indication that below the folding the main part of the crust has buckled downwards. So in our area the Earth's crust appears to give way by faulting and not by buckling or folding and this seems to point here to a rather thick rigid crust. If we apply to the crust the equations of the theory of elasticity as a sufficient approximation to its behaviour, we find that a horizontal compression can only bring about a buckling of the crust if its thickness does not exceed a certain limit or if it separates in layers each of limited thickness. If the thickness exceeds these limits a compressive stress can only give shearing. So we may probably conclude to the presence of a rather thick rigid crust in the area under discussion. This seems to be in good harmony with the conclusion arrived at in a recent paper [1]) on the gravity over and near the Hawaiian Archipelago and Madeira, where the writer derived a thickness of at least 25 km for the crust when consisting of one layer only.

In case of shearing along planes in two directions we may reasonably suppose the presence of a compressive stress parallel to the bisector of the angle between the directions. A few years ago BYLAARD [2]) has derived the angle the two shearing planes

[1]) F. A. VENING MEINESZ, Gravity over the Hawaiian Archipelago and over the Madeira area; conclusions about the Earth's crust, Proc. Ned. Akad. v. Wet. Amsterdam, **44**, 1 (1941).

[2]) P. P. BYLAARD, De plastische vervorming van vloeiijzer en de berekening van ijzerconstructies, De Ingenieur, 23 (1933).

P. P. BYLAARD, Théorie des déformations plastiques et locales par rapport aux anomalies de la gravitation, aux fosses océaniques, aux géosynclinaux, au volcanisme, à l'orogénie et à la géologie de l'océan pacifique occidental, Association de géodésie, rapport du congrès d'Edinbourg (1936).

may be expected to make if the shearing takes place in a plate of an elastic material after the strength limit has been passed and plasticity has set in. He found an angle of 110° involving an angle of 55° between the stress direction and each of the shearing planes. As this condition of plastic shearing is probably fulfilled in the crust, the fact that the two directions shown by the topography do indeed enclose this angle seems a good corroboration of our hypothesis. Adopting it we would find the direction of the compression of the crust to have an azimuth of about 10° west.

Such a compression does not appear unlikely. If we admit the presence of a rigid crust under the Atlantic, we may expect similar stresses in that crust to those having caused the great crustal shortening in Europe by the Alpine orogeny. These features break off at the western shores of the continent and it seems indicated to suppose that the adjoining oceanic crust has undergone a similar shortening. The difference of constitution and eventually also of thickness of the continental and the oceanic crust may well have caused a different behaviour in giving way to these stresses. As a consequence of this hypothesis we must suppose that not the entire topography is volcanic but that part of it must have originated because of the thickening of the crust by this compression. Examining the map of the central and eastern group of the Azores, we get the impression that while the volcanoes preferentially occur in the direction WNW—ESE this other topography also occurs in the second direction. Clear evidence that tectonic phenomena are present in our area besides volcanism is also given by the seismic activity in the Azores as well as over the Mid Atlantic rise and between the Azores and Europe. We find such evidence likewise in the geomorphological and geological indications for vertical movements found in many islands. Those e.g. belonging to the Azores archipelago have been tilted westwards; the eastern parts show more effects of erosion and so are evidently older than the western parts. In Santa Maria middle miocene marine limestone is found at elevations ranging from 40 m to 120 m [1]).

The interpretation of the gravity anomalies in our area is not easy. Marked features of strong anomalies do not occur except on the islands and here they disappear by applying regional isostatic reduction [2]). So we require a more detailed gravimetric survey for getting insight in the anomalies than e.g. in the East Indies where the presence of the belt of large negative anomalies allows to trace its course by means of profiles at great distances from each other. Another consequence of the smaller size of the anomalies is the greater relative effect of the errors in the isostatic reduction resulting from a defective knowledge of the submarine topography. So we need a still larger number of observations in this area before a satisfactory gravimetric study will be possible. At this moment most of our conclusions cannot be otherwise than tentative.

The whole gravity material has been subjected to the reduction by means of the new tables for regional and local isostatic reduction according to the Airy system [3]). They have been reduced for values of the crustal thickness T of 20 km and 30 km. The accompanying map shows two sets of the anomalies for $T = 30$ km viz. one for local compensation and the second for a spreading of the compensation over an area up to a radius R of 116.2 km; the last set has been underlined. In the near future the writer will give a more detailed investigation of our area in the report about all the gravity results obtained at sea to be published by the Netherlands Geodetic Commission; this will contain more anomaly maps as well as gravimetric profiles. Here we shall only give a short summary of this investigation.

A careful study of the different sets of anomalies shows that part of the topographic features seems to be more or less locally compensated and another part regionally. For Madeira the former investigation already mentioned has shown that the anomalies point

[1]) Dr. FR. V. WOLFF, Der Vulkanismus, Bd. II, pp. 959 and 971, Stuttgart, 1931.

[2]) For Madeira see the first foot-note on the preceding page.

[3]) F. A. VENING MEINESZ, Tables for regional and local isostatic reduction (Airy system), Publ. Neth. Geod. Comm. Waltman (Mulder), Delft, 1941.

to a large degree of regionality. Adopting the island to consist of heavy volcanic material of a density θ of 2.937 we obtain a value of R of 232.4 km and putting θ at 3.07 we find 174.3 km. A similar result has been found for Hawaii, Oahu, Bermudas, São Vicente (Cape Verde Is), Canary Is and Mauritius. In view of these results on volcanic islands it is remarkable that those islands of the Azores where gravity has been observed, i.e. São Miguel and Fayal, show a much smaller degree of regionality. Adopting the same values for the density θ we find the anomalies on São Miguel to get into harmony with those in adjacent waters for a value of R of less than 100 km, while for Fayal the results give no clear indication but probably they point to a still smaller degree of regionality. It appears to the writer that we can well understand this difference from the situation for other volcanic islands; we could explain it by the many fault-planes in the Azores reducing the coherence of the crust.

The same uncertainty as found for Fayal is experienced when studying the results for the submarine banks west of the Iberian peninsula. As the map shows gravity profiles have been made for the Josephine Bank and for the submarine promontory west of Cape Finisterre. Over the first bank the profile to the west seems to indicate regional compensation and that to the north local compensation. Over the second the southern profile appears to show local and the northern one regional compensation. Here also we probably may attribute this irregular result to faulting which in some directions diminishes the crust's resistance to local adjustment.

During one of the expeditions pairs of stations have been observed at small distances of about 10—20 km from each other. This occurred during the winter voyage of Hr. Ms. O 16 which took place in unusual bad weather. This induced Captain VAN WANING to give his crew from time to time a few hours of rest and a quiet meal by staying submerged during a longer time than usual. The writer availed himself of this opportunity to repeat the observations at the end of this time. We find two of these pairs to the NW and to the W of Cape Finisterre, one near Terceira, one to the SSW of Fayal, one near Flores and one to the SW of the Azores at about 34½° N.L. It is interesting to see that nearly all these pairs show considerable differences of depth and so they make it possible to study the way of isostatic compensation of these irregularities in the topography although the mean error of 5—8 milligals does not allow strong conclusions. Still the map shows that nearly all of them point to regional compensation. Only the pairs to the SSW of Fayal and to the SW of the Azores do not allow a conclusion as the difference of the two anomalies do not vary much for the regional and the local reduction. The final report will contain the detailed results for these pairs of stations and will give the anomalies for all the reductions. The fact that these irregularities in the topography appear to be regionally compensated seems to point to their not having been brought about by faulting along vertical fault-planes which would probably lead to more or less local compensation. They may have been caused by volcanic activity but also by faulting under lateral compression along tilted planes; both these origins may be expected to bring about regional compensation.

To the west of the Azores, i.e. to the west of the Mid Atlantic Rise and about parallel to it, a series of stations over deep water shows positive anomalies; the sea-depth ranges here from 4000 to 5000 meters. The amount of these anomalies is smallest for the local reduction and the WE gravimetric profile across it gives the same result; for the regional reduction, especially for large values of R, this profile shows a bulge of larger positive anomalies to the west of the Mid Atlantic Rise and this disappears for the local reduction. For $T = 20$ km this is still more the case than for $T = 30$ km. So this seems to indicate that the Mid Atlantic Rise is locally compensated corresponding to small values of T.

As the map shows, a similar result follows from the profile to the SW of the Azores at about 34° N.L.; the three stations to the left, over the western slope of the Mid Atlantic Rise, show better agreement for local than for regional reduction. Other crossings at latitudes of 23° N.L. and 10° N.L. give the same result although the great distance of the stations and the uncertainty of the submarine topography does not allow a strong conclusion. Still the mutual agreement of all the profiles gives us some confidence that our result is justified.

About its meaning we may make more than one supposition. In the first place it may mean that this western slope of the Mid Atlantic Rise has the same character as the slopes of the edges of the continents. In a previous paper [1]) the writer has mentioned the gravity results observed over these slopes. Nearly all of them give the same result; they show these slopes to be locally compensated according to small values of the crustal thickness T of 20—30 km. The most obvious explanation, in harmony also with the seismic results, is to suppose the granite layer of the crust to become suddenly much thinner at the edge of the continent or even to disappear there. As it is generally admitted that in the central and eastern Atlantic a granite layer is present in the crust, it might be possible that the explanation also applies to the western and eventually also to the eastern slope of the Mid Atlantic Rise. The small values found for T rather point in this direction. We may, however, also suppose a relative movement in vertical sense along a vertical fault-plane of the Rise with regard to the area west of it brought about by some change of density, a sinking of the last part or a rising of the first. This would likewise involve a local isostatic compensation of the slope.

These are the main results obtained by the comparison of the anomalies according to local and regional reduction. We shall now consider other features of the anomaly fields.

In the first place we have already mentioned that notwithstanding the seismicity of our area no trace is found of belts of strong negative anomalies similar to those found in the East and West Indies and near Japan. This is a strong indication that the tectonic phenomena in our area have a different character and that there is no question here of a downward buckling of the Earth's crust nor probably of folding and overthrusting of the surface layers.

In the second place an important feature of the anomaly-field is the presence of fields of positive anomalies all showing a striking correlation with the topography; they more or less coincide with elevated parts of the ocean-floor. This is e.g. clearly shown by the area of the Azores where the line of + 30 milligal in the map of the locally reduced anomalies can be compared to the contour-line of 3000—4000 m depth. They do not exactly coincide and in some cases the anomalies extend somewhat further than the elevation, e.g. to the NE of São Miguel, but the correlation can not be doubted. Other examples are given by the ridge to the NE of the Azores, by that of the Gorringe Bank and the Josephine Bank, by the bank to the W of Cape Finisterre and by the short E—W ridge of Madeira. This does not mean a close correlation of the elevation and the anomalies; the higher elevations, e.g. the islands of the Azores and Madeira and the high banks, do not show corresponding high positive anomalies, even not in the field corresponding to local compensation. The correlation seems more to have regard to the regional elevation than to the local topographic features. Its being more or less independent of the type of reduction, local or regional, points in the same direction.

It is difficult to find an explanation of this disturbance of the isostatic equilibrium as well as of the remarkable correlation to the regional topography which seems too clear to be fortuitous. In connection with the volcanic processes at the surface we might suppose these anomalies to be caused by the rising of heavy magmatic material in the deeper layers bringing about a rising of the whole area without the isostatic adjustment keeping pace with it. This would imply a fairly great speed of the phenomenon but this of course would apply to other explanations as well. The mean anomaly in the area of the Azores of + 45 milligal corresponds to an uncompensated rock-layer of 580 meters of a density of 2.67 (to be diminished for the computation by the density of sea-water of 1.028). Applying to these data the formula for the readjustment of isostatic equilibrium

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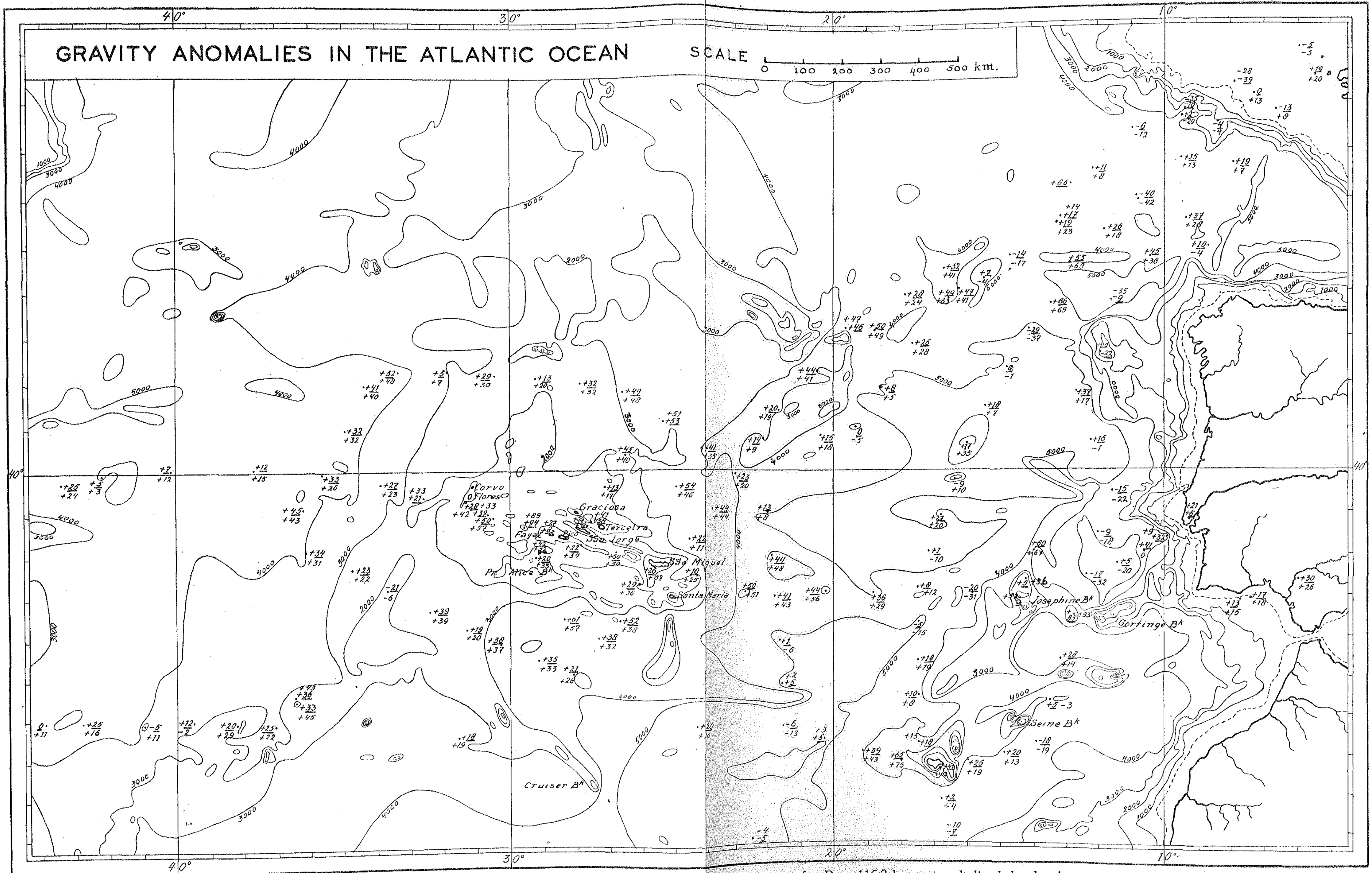
[1]) F. A. VENING MEINESZ, Gravity over the continental edges, Proc. Ned. Akad. v. Wetensch. Amsterdam, **44**, 8 (1941).



Isostatic anomalies for a thickness of the crust T of 30 km, underlined: regional reduction for R = 116.2 km, not underlined: local reduction.

derived by the writer from the post-glacial uplift of Scandinavia [1]) and introducing in these formulas a diameter L of 400 km, we find the sinking we might expect if no other phenomena were taking place to be about one cm pro year. This may give an idea of the speed of the phenomenon needed for counterbalancing this sinking and keeping up the positive anomalies in their present size. The geological evidence on the islands of the Azores does not appear to point to a sinking but rather to a rising and these movements seem to be irregular and of a smaller amount than the above figure. Generally speaking the eastern parts of the islands seem to have risen more than the western parts and the eastern islands more than the western.

The tentative explanation mentioned above goes more or less in the same direction as the hypothesis given by CLOOS [2]) in an investigation mainly based on the geometrical pattern of the topography in the Azores, but with this difference that CLOOS looks upon the rising magmatic bulge in the archipelago as the cause of the faulting and of the volcanism because of the tension it brings about in the crust, while the writer, considering the two directions apparent in the submarine topography of the whole area from the Azores to Europe as mentioned in the beginning of this paper, is inclined to think the faulting to be the primary cause and the rising of the magma together with the volcanism to be brought about by the presence of these fault-planes.

For the further investigation of these interesting problems it is important to make more soundings and a more detailed gravimetric survey of these areas of positive anomalies in order to get a better idea of the character and extension of these fields and of their correlation to the topography.

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[1]) F. A. VENING MEINESZ, The determination of the Earth's plasticity from the post-glacial uplift of Scandinavia, Isostatic adjustment, Proc. Ned. Ak. v. Wet. Amsterdam, 40, 8, p. 662 (1937).

[2]) H. CLOOS, Zur Tektonik der Azoren, Abh. Preuss. Akad. d. Wiss. Phys. Math. Kl. 1939, 5 (see foot-note first page).