# GRAVITY EXPEDITIONS AT SEA

1923—1932.

#### VOL. II.

REPORT OF THE GRAVITY EXPEDITION IN THE ATLANTIC OF 1932

AND

#### THE INTERPRETATION OF THE RESULTS

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This edition was reprinted from the first edition published in 1934, using a photo-mechanical process. In view of the costs involved the detailed data of the isostatic reductions, included in the first edition in a separate envelope (see Preface page 2), and the coloured maps added at the end of the first edition were not reprinted.

The details of these maps are as follows:

#### Bathymetric World Map

This map shows the location of the gravity stations No. 1—168 and No. 426–486. The coordinates of these stations are given in page 89–95. Moreover maps showing the stations in the Atlantic Ocean and the Indonesian Archipelago are also included in: Vening Meinesz, F. A., Gravity Expeditions at Sea, 1923–1938, Volume IV, Publication of the Netherlands Geodetic Commission, Delft, 1948.

#### Gravimetric-Geological Map of the Indonesian Archipelago (see chapter VI)

A similar map is included in: F. A. Vening Meinesz, Gravity Expeditions at Sea, 1923-1938, Volume IV.

#### Bathymetric Chart of the Indonesian Archipelago

This map is also published in: Riel, P. M. van, Snellius Expedition, Bathymetric map of the Indonesian Archipelago, Volume 2, Oceanography, part. 2, Kemink en Zoon, Utrecht 1935.

#### PREFACE.

The interpretation of gravity anomalies is a subject about which the opinions are yet divided. This results from its many-sided character. The problem has no unique mathematical solution and so only the combination of the gravity data with data from other sides — in the first place geological and morphological data — can provide us with an interpretation that has a chance of being near the truth. So the cooperation of the geodesist with the geologist is imperatively required; an independent investigation of one of them risks to neglect facts and view-points that can only be known to the experienced specialist in his own branch.

The writer feels sincerely indebted to Dr. J. H. F. Umbgrove, Professor of Geology at Delft, for having been willing to take up this subject and to cooperate with the writer in trying to find an adequate interpretation of the gravity data in the East Indies. His wide knowledge of the subject guarantees the proposed solution to be compatible with what is known nowadays about the geology of this area. Chapters VI and VII contain the results of his important and comprehensive study.

The writer wishes likewise to acknowledge gratefully the cooperation of Mr. P. M. VAN RIEL, Director of the Meteorological Institute of De Bilt, and of Dr. Ph. H. KUENEN, Geologist at the University of Leiden, resp. Leader and Member of the Oceanographic Expedition of the "Willebrord Snellius", which investigated the Eastern part of the East Indian Archipelago in 1929 and 1930. The first has kindly permitted that the bathymetric map of the Archipelago, which for its eastern part is entirely based on the great number of soundings of this expedition, is published in this report, although the report of the Snellius Expedition regarding these soundings will only appear a few months later. For all details concerning the soundings and the interpretation of the depth-contours, the reader may be referred to Vol II, part 2, of the report of the Snellius Expedition.

To Dr. Kuenen the writer is obliged for his valuable morphological contribution of chapter VIII of this publication. It treats of the morphology of the archipelago and shows that the interpretation of the gravity anomalies is in harmony with it. For further details we may refer to the more exhaustive study of Dr. Kuenen in Vol V, part 1, of the report of the Snellius Expedition.

For the minute care bestowed on the drawing of the coloured geological-gravimetrical map of the East Indian Archipelago, the writer is indebted to Mr. C. VAN WERKHOVEN of the Geological Institute of Delft and for the drawing of the bathymetrical map of the East Indies to Mr. C. CRAANDYK.

This second volume of the report is preceded by a theoretical chapter in which the writer has put together some general considerations and investigations regarding the subject of the interpretation of gravity anomalies. In an introduction to this chapter he has tried to give a summary of this subject for the not-geodesist.

Chapter II may be considered as the continuation of the first volume which has appeared two years ago and which treats of the gravity expeditions themselves and of the computation of the results; it contains the report of the gravity expedition in the Atlantic Ocean which has taken place since then. Its results have been added to the list of chapter III, which gives the results of the Bouguer reduction and of the isostatic reduction according to three different systems of reduction of all the 486 stations. In order not to burden this publication with too many figures the detailed data of these reductions have been published in a separate envelope.

Chapter IV gives a general survey of the results without going into possible interpretations. The conclusions of this chapter will probably be shared by all who study these results. An attempt at an interpretation is taken up in the remaining chapters of which V—VIII refer to the East Indies and chapter IX to the other areas that have been investigated. Chapters V—VIII have also been published separately.

For the acknowledgements to the Minister and other authorities of the Netherlands Navy to whose cooperation this scientific research is entirely due, and to the Commanders, Officers and crews of the submarines on board of which the investigations have been made, the writer refers to the Preface of Volume I of this publication.

F. A. VENING MEINESZ.

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#### CHAPTER I.

# Interpretation of gravity results. Theoretical considerations.

#### Part 1.

#### Introduction.

For the not-geodesist an introduction may be useful before going into details concerning the theory and practice of the interpretation of the gravity results. So a short discussion of the general features of gravity research may follow here.

The object of gravity research is twofold, the determination of the Figure of the Earth and the investigation of the upper layers of the Earth. The first will be treated more in detail in part 2 of this chapter and the second in part 3. We shall begin by examining the first of these objects, the determination of the Figure of the Earth, which has been the classical aim of gravity research and which, until a relatively short time ago, was the only one. When, in the seventeenth century, the pendulum investigations of Huygens had disclosed a possibility of measuring gravity with great accuracy, it was soon realized that this opened up a way for determining the flattening of the Earth and since that time this method has been often applied. In the latter half of the former century the investigations have been taken in hand by an increasing number of countries and now gravity is already known in nearly five thousand stations on Earth.

The expression, the Figure of the Earth, means the shape of the surface at mean sealevel, that everywhere is perpendicular to gravity. This surface is called the geoid. At sea, it coincides with the mean ocean surface, i.e. the surface of the water if not disturbed by winds, by deviations from the normal atmospheric pressure or by tide-effects. On land it coincides with the position of mean sea-level. It is not surprising that gravity can be used for determining the shape of the geoid. When we realize that the geoid is defined by its being everywhere perpendicular to gravity, in other words by its being an equipotential surface of the gravity field, it is evident that geoid and gravity are both features of the same gravity field and it is not unexpected that they are connected by an equation. In part 2 of this chapter we shall go deeper into this relation.

It is well-known that, as a first approximation, the good is a rotation ellipsoid with the short axis, the rotation axis, coinciding with the axis of rotation of the Earth. At the meeting of the International Geodetical and Geophysical Union at Madrid in 1924, the following dimensions have been adopted as the best approximation to the geoid:

Equatorial Radius: 6.378.388 meters.

Flattening: 1/297 (Diff. of Equat. and Polar Radius).

This standard ellipsoid or ellipsoid of reference was deduced by Hayford from measurements of arc but it is likewise in good harmony with the complete gravity material.

It is not doubtful, however, that the geoid is not exactly represented by this ellipsoid. Besides local deviations, there probably exist deviations of some hundred meters elevation or more, extending over great parts of the Earth's surface. The problem of the Figure of the Earth is nowadays to determine these deviations. In the same way as was the case for the determination of the ellipsoid of reference, this can be done in two ways, by astronomical observations in connection with triangulations and by gravity determinations. We shall consider both methods.

When applying the first method, we determine astronomically the position of the true vertical, i.e. the direction of gravity, in a number of places, of which the relative positions are known by triangulation. As the geoid is perpendicular to the direction of the vertical, we obtain it by constructing a surface, that in all these places is perpendicular to the observed positions of the vertical. It is clear that we get in this way the geoid for the area where our measurements have been made. Three things, however, must be remembered

First, it is necessary to make observations of the vertical in a great number of stations at rather small distances, because the construction of the surface, starting from one point and going along from station to station, is dependent on our knowledge of its slope everywhere. This can of course only be realized up to a certain degree and so we have to interpolate the slope between the observations. The resulting uncertainty for the geoid gets greater and greater at greater distances from the starting point.

Secondly, the method does not provide the absolute position of the geoid with regard to the ellipsoid of reference. The surface that is found, can for instance be shifted up and down as a whole without disturbing the perpendicularity to the vertical in the observed stations. But it is likewise impossible to fix it in its horizontal position on the ellipsoid, because we cannot extend our observations over the whole Earth. Besides the practical difficulties, the oceanic parts prevent all triangulation and exact astronomical observation, and so we cannot connect one part of the geoid with another similarly determined part. In these circumstances we cannot fix those separate parts of the geoid with regard to the ellipsoid.

Thirdly, the oceanic parts of the good cannot be found at all with this method.

The second method of determining the geoid by means of gravity determinations, has been rendered possible by the deduction by Stokes of a theorem, which gives the relation to gravity of the distance between geoid and ellipsoid. In Part. 2 of this chapter we shall examine this theorem more in detail. When we know gravity, we can therefore compute this distance everywhere and so we can deduce the position of the geoid with regard to the ellipsoid.

This method, however, has also a disadvantage. The distance from geoid to ellipsoid at a station is not only a function of the gravity at that point, but it is likewise dependent on the gravity at all other points of the Earth's surface. Rigorously speaking, it could not, therefore, be applied, if we did not know gravity over the whole Earth. There is no doubt, that this objection is largely responsible for the fact that this theorem has not yet been used.

The difficulty is not, however, so insuperable as it may appear. The fact is that, although

gravity at great distances from the station does also enter into the formula, it has only a small effect; for a well-chosen ellipsoid the main part of the distance from geoid to ellipsoid at a station is given by the values of gravity in the neighbourhood of that station. So a gravity survey of a certain area may already give a fairly good approximation to the shape of the geoid in the central part of that area, although gravity is yet unknown in other parts of the Earth. This approximation is still better because of the fact that the principal part of the effect of distant areas is to shift the computed part in a slightly different position with regard to the ellipsoid, without much affecting its shape. The position with regard to the ellipsoid is therefore slightly less sure than the shape, but the uncertainty of this position is much smaller than when we apply the first method.

Another important point about this method of determining the geoid, is the fact that gravity observations can also be carried out at sea. This provides us with the means to find the geoid likewise for the oceanic parts of the Earth's surface and so this method enables us to solve the entire problem of the Figure of the Earth. Of course this solution is yet remote; we shall have to wait till the whole Earth has been surveyed gravimetrically.

It is clear that the Figures of the Earth, given by both methods, must agree with each other; they can never give different results. Eventual contradictions can only be explained by errors of observation or deduction. It is a wrong view that one method can supplement the other by giving data that could not be obtained by means of the other method. The methods can only check each other.

It may be that the object of determining the Figure of the Earth is not to obtain this figure in itself, but to investigate eventual deviations from equilibrium of the Earth by comparing the observed figure with the shape that it ought to assume when it should be in equilibrium under the double effect of the rotation round its axis and the mutual attraction of its constituent parts. If this is the object the question may be put whether there is any sense in first determining the Figure of the Earth from the gravity results and afterwards concluding to eventual deviations from equilibrium. We may just as well use gravity at once for investigating the conditions of equilibrium; in the following pages and in part 3 of this chapter we shall consider this line of research in detail. It is a more direct method, which gives clearer insight and more precise results.

This method of investigating the Earth, or practically speaking its upper layers, tries to deduce data from the gravity field about the distribution of its masses. This possibility follows from the fact that gravity, being the attraction by the masses of the Earth, is a function of these masses and their position with regard to the gravity station.

This line of research was inaugurated in the second half of the former century by the discovery of isostasy by the British geodesists in India and by their interpreters AIRY and PRATT. It was not actively pursued during the next period till the interest was stimulated again when HAYFORD and BOWIE took up this subject in the beginning of this century. Although much has been done since then, it can safely be said that these investigations are still in their infancy and that much may yet be expected from them.

In recent years, the research has also developed in a new direction, i.e. towards the detailed investigation of the superficial layers of the Earth's crust by means of the study of the local deviations of the gravity field, which can easiest be found with the Eötvös balance. It is well-known how important this possibility has become for geophysical prospection. This branch of the gravity research however, lies outside the scope of this publication.

The usual method for drawing conclusions from gravity about the distribution of masses in the Earth, is to compare the observed values of gravity with the formula for normal gravity, i.e. to compute the gravity anomaly with regard to this formula. The formula can be considered to be the attraction of gravity on the geoid of a theoretical Earth, of which the masses are in perfect equilibrium under the effects of rotation and mutual attraction and that has neither topography outside the geoid nor irregularities inside it.

Adopting a certain distribution of density between surface and center of the Earth, that is in agreement with the seismological data, we can compute the shape of this theoretical Earth and we find that it differs only very slightly from a rotation-ellipsoid with the same flattening; when the dimensions of this ellipsoid are judiciously chosen, the greatest distance between both surfaces amounts only to a few meters. The ellipsoid of reference of page 8 may thus be considered to be a good approximation to the geoid of our theoretical Earth. Because of the mathematical simplification obtained by using an ellipsoid as surface of reference, these small deviations are neglected and, maintaining the ellipsoid as surface of reference, we consider it at the same time as geoid of our theoretical Earth.

The mathematical relation between geoid and gravity field, of which the theorem of Stokes is the expression, allows to compute the gravity field corresponding to the ellipsoid of reference, save a common factor, which we can still choose and which we can adapt to the gravity material that has been observed. Cassinis has done this and found the following formula

$$\gamma_0 = 978.049 (1 + 0.0052884 \sin^2 \varphi - 0.0000059 \sin^2 2 \varphi)$$

in which  $\varphi$  is the latitude. This formula can be considered to be the gravity on the geoid of our theoretical Earth; if we compute it from the density assumptions, that are mentioned above, we find a value that hardly differs more than 1 milligal and so we can safely neglect this difference. The formula of Cassinis has been adopted for normal gravity by the meeting of the International Geodetical and Geophysical Union at Stockholm in 1930.

An important point is that this formula is in good agreement with the gravity results that have been found up to now. It follows from this fact that these results are also in good agreement with the ellipsoid of reference, which corresponds to this formula. We mentioned this fact already on page 8 where we gave the dimensions of the ellipsoid.

The formula for normal gravity gives gravity on a theoretical Earth, of which the outer surface coincides with the ellipsoid of reference. For comparing the observed gravity to these values, we should wish to reduce our observed values to the same surface, i.e. to compute the value, that we should have found if we had made the observation on the ellipsoid instead of at some elevation above or below it. This presents difficulties. As we know the way in which gravity varies with the elevation outside the Earth, we are able to shift our station over a given vertical distance. We can thus reduce our observations to the geoid of the actual Earth, because we know the elevation of our station above or below it. But we don't know the elevation of our station above or below the ellipsoid of reference because we usually don't know the position of this ellipsoid with regard to the geoid, and so we cannot make the reduction of our observation to the ellipsoid.

When we compute our gravity anomaly in the usual way by comparing the observed value, reduced to the geoid, to the value of normal gravity, part of this anomaly is due to neglecting the reduction from geoid to ellipsoid. We will examine this point in detail in part 2 of this chapter and we shall see there that, according to the theorem of Stokes, the mean

anomaly over a certain area will usually increase when we take this reduction into account. It can safely be stated that the reverse can practically never occur in such a degree, that the anomaly would disappear in this way. We can also put it thus, that the anomalies can practically never be explained by the deviations of the geoid from the ellipsoid.

The anomalies must evidently be due to the difference between the actual Earth and the theoretical Earth. We shall call the deviations of mass between both bodies anomalous masses. They have two effects on gravity, firstly the direct effect determined by the field of attraction, and secondly the indirect effect brought about by the above deviations between geoid and ellipsoid because these deviations are likewise the consequence of the presence of those masses.

Part of the anomalous masses are the topographical masses at the Earth's surface and the defects of mass in the seas and oceans. Save a slight uncertainty as to their density, we know these topographical masses and defects and we can compute their direct and indirect effects. The remaining part of the anomalies is due to the unknown mass-irregularities in the Earth and we wish to derive these last mass-deviations. This would solve our problem to deduce the constitution of the Earth from the gravity field.

Theoretically this problem has no fixed solution; there is an infinity of mass-distributions giving the same field of attraction at the Earth's surface. Practically, however, there are limitations for our solution given by limits for the densities and by other considerations. This renders it feasible to arrive at important conclusions regarding the distribution of the masses in the Earth but we shall always have to realize that our conclusions are not rigid. Generally speaking, we never can go further than the statement that a certain distribution of mass is possible. A proof that it is the actual one, can never be derived from gravity alone. So it is clear that an interpretation of gravity results without making use of the results of other lines of investigation, as for instance seismology, geology and geophysics, has no value.

It follows from this character of the problem that we shall often have to find our solutions by trying different possibilities of mass-distribution and seeing how far they answer the purpose. For making it easier to find the attraction of a certain distribution that we wish to try, a method and two tables will be given in part 3 of this chapter; they refer to two cases which occur often, a two-dimensional distribution of masses extending over a great distance in the direction of the third dimension and an axially symmetrical distribution.

The underlying principle, that is at the root of all our investigations, is the well-known principle of isostasy. The physical interpretation of this principle was already given in the middle of the last century by AIRY; he explained it as the effect of the crust being in floating balance on the lower plastic sima-layer. A large amount of confirmatory evidence allows to accept this condition as the normal one for the Earth's crust and we shall find further confirmation of this assumption in the great number of gravity values at sea.

Two important lines of investigation are derived from this principle: How is the isostatic balance of the Earth's crust realized in different regions? And secondly: Are there any deviations from isostatic equilibrium and what is their meaning? These two great problems will dominate our discussions and interpretations.

The first problem can be considered as a geometrical problem. The isostatic equilibrium requires mass-deviations in the upper layers of the Earth, that compensate the mass-irregularities due to the topography, i.e. the topographic excesses of mass outside the geoid and the defects of mass inside the geoid in the ocean-basins. The point to be investigated is the localization of these compensating mass-deviations and this gives the problem its geometrical character.

If we assume purely local compensation that is to say if we suppose every vertical cylinder of the crust of the smallest horizontal cross-section to be in independent equilibrium, the compensating masses have to occur in the same vertical as the corresponding topography. In that case we should only have to find out the depth of these masses. But this assumption of local compensation is improbable and so we have to consider it likely that they may occur at least partly besides the vertical of the corresponding topography and this introduces also an uncertainty of localization in horizontal sense.

The way to attack this problem has been first indicated by HAYFORD and BOWIE in their extensive studies of the different features of isostasy. We assume a certain system of distributing the compensating mass-deviations and we compute their attraction in the stations where the gravity observations are made, in order to find out whether this distribution answers the purpose. For accurate conclusions we must likewise take into account their indirect effect, caused by the alteration of the geoid, which they bring about. In part 3 of this chapter we shall examine in detail the three systems that have been applied in this publication. The first is the system of HAYFORD-BOWIE that assumes local compensation, evenly distributed between sea-level and a certain depth, called depth of compensation, in this case 113,7 Km. The second is the system of Heiskanen, founded on the principle of Airy; it assumes local compensation of mountains by means of roots of light crustal material at the lower boundary of the crust, which displace the heavier simatic material, in the same way as ice-bergs keep in equilibrium because of a root of ice displacing the heavier water. The third is a system elaborated by the writer, which does not assume local compensation but which spreads the compensation over a greater area, localizing it vertically in the same spot as HEISKANEN does, i.e. at the lower boundary of the crust.

These investigations, combined with the study of the Bouguer anomalies, which still contain the field of attraction of the compensating masses, may give us in many instances an idea about the way in which these masses are distributed. This knowledge is of importance for getting insight in the processes in the crust, that have brought about the topography at the Earth's surface and the geological features of the upper layers of the crust. We shall examine these problems in chapter V, which treats of the interpretation of the gravity results in the East Indies.

The second problem about eventual deviations from equilibrium has a physical character; the corresponding investigations don't necessarily study the way in which the masses are distributed but they focus the attention on causes and stresses that must be assumed for explaining these deviations. We shall only discuss in this connection deviations of great horizontal extension, because smaller irregularities of mass in the crust, that can be carried by the crust without its giving way by shearing, will not be considered as deviations from equilibrium; if we did not make this distinction, every topographical feature should have to be included.

Extensive deviations from isostatic equilibrium of the crust are revealed by extensive fields of anomalies of the same sign. The study of these fields promises not only to be of great importance for our views about the great phenomena acting in the Earth, but likewise for the study of the Figure of the Earth. This follows from the fact that only extensive anomaly-fields perceptibly affect the shape of the geoid given by the theorem of Stokes. This leads us to the conclusion that the principal object of Geodesy, the determination of the Figure of the Earth, is intimately connected with the physical conditions prevailing in the Earth. So an increase of knowledge about these physical processes will be desirable for attacking this great problem more judiciously than has been the case up to now.

#### Part. 2.

## Determination of the Figure of the Earth; Reduction of gravity from Geoid to Ellipsoid.

The Figure of the Earth is the shape of the geoid, i.e. the shape of the potential surface of the gravity field at mean sea-level. Potential Theory procures the means to compute this potential surface if the value of gravity on this surface is everywhere known.

Under simplified conditions this relation of geoid and gravity is already known a long time. The well-known formula of CLAIRAUT is its first formulation; it assumes that the geoid is a surface of revolution round the axis of rotation of the Earth and it gives the relation between the flattening of the geoid and the difference of gravity at the poles and at the equator.

It is not doubtful, however, that the assumption of the geoid being a surface of revolution, is only an approximation that does no longer satisfy the modern requirements of precision. It is possible to do without this assumption; in the middle of the past century Stokes has already deduced a Theorem, that gives a perfectly general solution without any assumption about the geoid, save the obviously true fact that in rough approximation it is a sphere. Since then, Helmert, Poincaré and several others have likewise taken up this problem; their investigations confirmed the validity of Stokes' Theorem.

It can safely be stated that this theorem is one of the most important foundations of geodetic science. We mentioned already in the introduction that it is only along this line that we may hope to determine in the future the complete geoid, because the other method, by means of measurements of arc, fails us over the ocean parts of the Earth. No clear insight, moreover, regarding the relation of deviations of the vertical and gravity anomalies can be obtained without it.

We can write the theorem of STOKES in the following shape:

$$N = \frac{R}{gS} \int_{0}^{S} F \Delta_0 dS \tag{1 A}$$

in which N = Distance in a point P from the geoid to the surface of reference,

R = Mean Radius of the Earth,

S =Surface of the geoid  $= 4 \pi R^2$ ; dS element of this surface,

g = Mean value of the gravity on the geoid,

 $\Delta_0 = \text{Gravity Anomaly in the element } dS$ ,

F = Function of the angle  $\varphi$  between the Earth's radii of the point P and the element dS:

$$F = \csc \frac{1}{2} \varphi + 1 - 6 \sin \frac{1}{2} \varphi - 5 \cos \varphi - 3 \cos \varphi \lg \left[ \sin \frac{1}{2} \varphi \left( 1 + \sin \frac{1}{2} \varphi \right) \right]$$
 (1 B)

The gravity anomaly  $\Delta_0$  must be computed with regard to a formula of normal gravity, corresponding to the surface of reference used for measuring N. This means that this surface of reference must be the potential surface of a theoretical Earth of which the masses are all inside this surface and of which the gravity on this surface is given by the formula for normal gravity. As surface of reference we will adopt the ellipsoid given on page 8 and as formula for normal gravity the formula of page 10; these assumptions conform to this requirement.

The theorem of Stokes is only valid if all the masses of the Earth are inside the geoid. This is an important point because, evidently, the Earth does not fulfill this condition. We can, however, avoid this difficulty by imagining a modified Earth, that is identical with the actual one save that all the masses outside the geoid are omitted or transferred inside the geoid. We can then apply the theorem of Stokes and deduce its geoid and afterwards we can determine the geoid of the actual Earth from that of the modified one.

The removal of the outside masses or their transfer from the outside towards the inside of the geoid changes the gravity field as well as the geoid of the Earth, but these modifications can be computed and this gives us the following programme. We apply the modification to the gravity data of the actual Earth and then we reduce them in free air to the geoid of the modified Earth. This material is used for applying the theorem of Stokes and so we get the geoid of the modified Earth. The last step is to deduce the geoid of the actual Earth by applying the shift of the geoid with contrary sign, that is caused by the removal or transfer of the masses.

We shall not further discuss here the different systems of modification of the Earth that may be used for this purpose, because we shall have to treat of these systems in detail in the next part. We shall then come back to our point and consider the changes of the gravity field and the shifts of the geoid that they bring about.

For discussing the theorem of Stokes it is desirable to consider the values of the factor F, with which the anomalies are multiplied in this theorem. For different values of the angular distance  $\varphi$  from P to the anomaly we find the following values for F:

$\varphi$	F	$\overline{\varphi}$	F	$\varphi$	$\overline{F}$
0°	∞				
1	+ 124.74	10°	+ 13.98	100°	— 1.26
2	+ 65.28	20	+ 5.50	110	0.58
2	+ 44.89	30	+ 1.90	120	+ 0.18
4	+ 34.40	40	<b>—</b> 0.17	130	+ 0.93
5	+ 27.92	50	— 1. <b>4</b> 0	140	+ 1.64
6	+ 23.47	60	<b>— 2.07</b>	150	+ 2.24
7	+ 20.20	70	<b>— 2.30</b>	160	+ 2.69
8	+ 17.67	80	<b>— 2.20</b>	170	+ 2.98
9	+ 15.65	90	— 1.83	180	+ 3.08

The integral of the Theorem of Stokes is the sum over the whole Earth's surface of the anomalies, multiplied by these factors and by the surface-elements to which they belong. A consideration of the table makes it clear that the effect of the anomalies is quickly diminishing with the distance till about  $20^{\circ}$ . For greater distances it remains at the same order of magnitude. It is positive till nearly  $40^{\circ}$ , i.e. for positive anomalies the geoid is outside the surface of reference. Then follows a wide belt of negative effects till about  $120^{\circ}$  and the remaining part gives again positive effects.

It follows from the great value of F for small distances that the position of the geoid depends principally on the anomalies in the vicinity of the station. If these anomalies are

positive, the gooid will in general be outside the surface of reference and incase they are negative, inside.

For computing the effect of the anomalies close to the station, we can better write the theorem in another shape by introducing the mean anomalies  $\Delta_m$  over circles round the station. For a circular ring of a width  $R d\varphi$  we have

$$\int \triangle_0 dS = 2 \pi R^2 \triangle_m \sin \varphi d\varphi$$

Introducing a new function of  $\varphi$  given by

$$F' = \frac{1}{2} \sin \varphi . F \tag{2 B}$$

the Theorem of STOKES takes the shape

$$N = \frac{R}{g} \int_{0}^{180^{\circ}} F' \Delta_{m} d\varphi$$
 (2 A)

For different values of  $\varphi$  we get the following table of the new function F'

$\varphi$	F'	$\varphi$	F'	$\varphi$	F'
00	+ 1.000				
1	+ 1.089	10°	+ 1.214	100°	— 0.623
2	+ 1.139	20	+ 0.941	110	— 0.261
3	+ 1.175	30	+ 0.475	120	+ 0.078
4	+ 1.204	40	<b>—</b> 0.054	130	+ 0.358
5	+ 1.217	50	— 0.538	1 <b>4</b> 0	+ 0.526
6	+ 1.227	60	<b>— 0.895</b>	150	+ 0.559
7	+ 1.231	70	1.082	160	+ 0.460
8	+ 1.230	80	- 1.084	170	+ 0.259
9	+ 1.224	90	— 0.91 <b>4</b>	180	0.000

As F' is nearly constant in the vicinity of the station, this shape of the Theorem is more appropriate for the computation of the effect of anomalies close to the station. It does not, however, give as clear a view as the first shape on the effect of a certain field of anomalies at greater distances from the station, because it is not the real anomaly  $\Delta_0$  that enters in the formula but a mean value  $\Delta_m$  which at great distance represents the mean over an extensive zone.

One of the uses that we can make of the Theorem is to compute the reduction of gravity values from the geoid to the surface of reference for taking away the part of the anomalies; caused by the deviations between both surfaces. This reduction is obviously the free air reduction over the distance N and so we get this reduction in the following two shapes

$$d_2 g = \frac{2}{S} \int_0^S F \triangle_0 dS$$
 (3 A)

$$d_{2} g = \frac{2}{S} \int_{0}^{S} F \Delta_{0} dS$$

$$d_{2} g = 2 \int_{0}^{180^{\circ}} F' \Delta_{m} dq$$
(3 A)

These formulas give the part of the anomalies caused by the deviation between geoid and surface of reference. This part has been denoted as the indirect part of the anomalies. We can make the same remarks with regard to this quantity  $d_2 g$  as we have done with regard to the deviation N. The effect of the anomalies  $\Delta_0$  is quickly decreasing with the distance for distances up to  $20^\circ$  and it is obviously depending principally on the anomalies in the vicinity of the station. If these anomalies are mainly positive, it is also positive, i.e. the direct or main part of the anomalies, caused by the attraction of the anomalous masses, is generally larger than the total anomalies.

This important conclusion is of course only true if there are no systematic anomalies over great extensions of the geoid, so that the combination of their effects can accumulate and counteract the effect of the anomalies in the vicinity. So we have to assume that the formula of normal gravity is well chosen and that no strong deviations of great extent from isostatic equilibrium are occurring. As all the present data point to the truth of these assumptions, we will continue our considerations on this base.

The predominating effect of the anomalies in the vicinity of the station is clearly demonstrated, when we compute N and  $d_2 g$  for a special case. We shall for instance suppose that there is an anomaly of + 10 milligal over a circular area of a diameter of  $10^\circ = 1112$  km and that the anomaly is zero for the remaining part of the Earth. In this case we find the following values for N and  $d_2 g$  for different distances  $\varphi$  from the center of the area.

$\varphi$	N meters	$d_2g$ mgal	φ	N meters	d <sub>2</sub> g mgal
0° 5 10 20 30 40 50 60 70 80	+ 6.46 + 4.17 + 1.71 + 0.68 + 0.24 - 0.02 - 0.17 - 0.26 - 0.28 - 0.27	$\begin{array}{c} + \ 2.0 \\ + \ 1.3 \\ + \ 0.5 \\ + \ 0.2 \\ + \ 0.1 \\ - \ 0.0 \\ - \ 0.1 \\ - \ 0.1 \\ - \ 0.1 \\ - \ 0.1 \end{array}$	90° 100 110 120 130 140 150 160 170 180	$\begin{array}{c} -0.23 \\ -0.16 \\ -0.07 \\ +0.02 \\ +0.12 \\ +0.20 \\ +0.28 \\ +0.33 \\ +0.37 \\ +0.38 \end{array}$	$\begin{array}{c} -0.1 \\ -0.0 \\ -0.0 \\ +0.0 \\ +0.0 \\ +0.1 \\ +0.1 \\ +0.1 \\ +0.1 \\ +0.1 \\ +0.1 \end{array}$

We see that in the center of this field of anomalies the geoid has an elevation of 6.46 meters above the surface of reference. On the edge of the field of anomalies, the elevation is still 4.17 m but at the double distance of the center, i.e. at  $10^{\circ}$  it sinks already to 1.71 m. At  $30^{\circ}$  distance it is less than 30 cm, at about  $40^{\circ}$  it is zero, at  $70^{\circ}$  it reaches a negative maximum of 28 cm, at  $118^{\circ}$  it is zero again and at  $180^{\circ}$ , i.e. at the opposite point of the station, it reaches again an elevation of 38 cm.

We see clearly that other fields of anomalies must be large and that they must be distributed very systematically in order to neutralize the elevation of 4 to  $6\frac{1}{2}$  m of the geoid

in the area of the above anomalies. Normally this will not be the case and so we may conclude that in general the geoid will be elevated above the ellipsoid in areas of positive anomalies and depressed in areas of negative ones.

Considering the reduction  $d_2g$  from the geoid to the ellipsoid, we get to an analogous conclusion, which we can formulate in the following important theorem:

When we reduce gravity from the geoid to the ellipsoid, the reduction has generally the same sign as the mean anomaly of the region, i.e. the mean anomaly of the region increases by this reduction.

We need not lay stress on the importance of this result. It means that we normally cannot explain gravity anomalies by deviations of the geoid. The taking into account of the indirect part of the anomalies tends, on the contrary, to enlarge the anomalies, caused by the attraction of the anomalous masses. We have demonstrated this for anomaly fields of some extension, but we can easily see that the same holds true for local anomalies; they cannot be explained by deviations of the geoid but in this case the increase of the anomalies by the removal of their indirect parts, or rather the increase of the differences of contiguous anomalies, is slight or negligible.

So we have generally to assume anomalous masses in a certain area of the Earth for explaining the gravity anomalies in this area, and for extensive fields of anomalies of the same sign these mass irregularities have to be somewhat greater than those of which the direct attraction would correspond to the anomalies.

The consideration of the values of F' in the equations 2 A and 2 B for values of  $\varphi$  smaller than 20°, gives us the means of deducing a formula for a rough estimate of N and of  $d_2g$  for the center of a field of anomalies of not more than 40° in diameter, provided we can neglect the effect of anomalies at greater distances. The table of F' on page 15 indicates that we can roughly assume F' to be constant over this area. Putting F' at 1,13, the formula 2 A and 3 B give

$$N = 0.0011 \ r \ \Delta'_m \ meters \tag{4 B}$$

$$d_2g = 0.00034 \ r \ \triangle'_m \ mgal. \tag{4 A}$$

in which r is the radius of the area in km, and  $\Delta'_m$  the mean in mgal of the mean anomalies  $\Delta_m$  of the different circular zones of the area.

In case we have for instance a circular area with a radius of  $1000 \ km$  and an anomaly of  $+50 \ mgal$ , these formulas give an elevation of the geoid in the center of 55 meter and an increase of the anomaly in this spot of 17 mgal when we take away the indirect part of the anomaly by reducing to the ellipsoid.

The examples that have been given may provide us with an idea of the order of magnitude of the deviations of the geoid, that accompany gravity anomalies of a given amount. It may be hoped that in the future it will become possible to apply the Theorem of Stokes in its full accuracy and to solve in this way the central geodetic problem: the determination of the Figure of the Earth.

#### Part. 3.

#### The Investigation of the upper layers of the Earth.

#### § 1. Introduction.

The investigation of the constitution of the upper layers of the Earth by means of gravity research can be done by comparing the gravity field of the Earth to the formula of normal gravity, or, more correctly expressed, to the gravity field of a theoretical Earth of regular constitution, whose geoid coincides with the ellipsoid of reference and for which the gravity on this geoid is given by the formula for normal gravity.

For comparing the gravity values of the actual Earth to this formula, we should wish to make these values directly comparable by reducing them to the same surface for which this formula is valid, i.e. to the ellipsoid of reference. This is usually impossible because we don't know the exact position of the ellipsoid with regard to the station and so we have to be satisfied by reducing them to sea-level, i.e. to the geoid of the actual Earth. The gravity anomalies found in this way are, therefore, composed of two parts, one part being caused by the difference of the fields of attraction of the actual Earth and the Theoretical Earth and the second part corresponding to the reduction from geoid to ellipsoid. The first will be called the direct part of the anomalies and the second the indirect part.

In the previous part of this chapter, we have considered the indirect part of the anomalies, the reduction from the geoid to the ellipsoid, and we have seen that this part is considerably smaller than the other one. So we don't make a great error in neglecting it as it is always done, but it is by no means negligible for precise conclusions. Secondly we have seen that generally the anomaly would increase when we should take it into account and that, therefore, the differences between the gravity fields of the actual Earth and the theoretical one are usually underestimated. It is not, however, impossible, as we shall see presently, to take this indirect part of the anomalies into account.

The differences of gravity as well as the deviations of the geoids of the actual Earth and the theoretical Earth are caused by differences of the constituting masses. If we assume the constitution of the theoretical Earth to be regular, we may call these differences the anomalous masses of the Earth. These masses bring about both the direct and the indirect part of the anomalies. The problem that we have to solve, is the determination of these anomalous masses when the field of anomalies is known.

This problem cannot be solved in a unique way; there is always an infinite number of solutions that are fulfilling the conditions. So no solution that is found can be considered as more than a possibility; it can never be proved, from gravity only, to be the true one. As we shall usually not be able to find more than approximate solutions which can only explain part of the anomalies, this uncertainty regarding the real situation is still more to be emphasized. We shall have to look for data from other sides, e.g. from geology, seismology and geophysics to check our solution; gravity alone is not sufficient to give it. Gravity gives an important contribution to our knowledge, but we have to be conscious of its limitations.

We can, however, express an important general rule for guiding our interpretations if we assume that the anomalous masses are only occurring in the upper layers of the Earth. This assumption is obviously probable, because all our geophysical considerations converge towards the assumption that the plasticity of the materials increases, when we get deeper into

the Earth. So deviations from equilibrium will be more and more unlikely for deeper layers and we may reasonably suppose our assumption to be true. We can then express the following rule:

The mean anomaly  $A_m$  in an area S that is great with regard to the thickness of the layer of anomalous masses but not more than about 5000 km in diameter, is practically only dependent on the total amount of these masses divided by S and not on their distribution.

It is easy to see the truth of this assertion for the main or direct part of the anomalies by realizing that approximately half of the total flux of lines of force of every mass-particle — for great areas slightly more — is flowing through the surface of the area, independently of its position. It is true that this approximation is getting less and less true for smaller distances of the mass-particle to the boundary of the area, but as the density of the anomalous masses is limited, these boundary errors are likewise limited and so these effects are small for sufficiently large areas. We neglect the effect on  $A_m$  of masses in other parts of the Earth.

Assuming that exactly half of the total flux of lines of force of all the mass-particles m is flowing through the surface S, we find the following formula, that expresses the above rule

$$A_m = 2 \pi k^2 \frac{\sum m}{S} = 4.19 \times 10^{-4} \frac{\sum m}{S} \text{ milligal}$$
 (5)

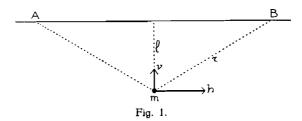
in which

 $k^2$  = Newtonion gravitation constant = 6.67  $10^{-8}$ 

m and S are expressed in gram and  $cm^2$ .

It follows from the above that this formula is approximate.

We can also prove the truth of the above rule by deducing the effect on  $A_m$  of displacements of a mass-particle m. Assuming that the boundary of our area is in the plane A B and that the particle is at a distance l below it, l being small with regard to the dimensions of the boundary, we find the following effects of vertical displacements v and horizontal displacements h of m.



Effect on 
$$A_m$$
 of  $\nu$ :  $\frac{2 \pi k^2 m}{S} \left[ \frac{\nu}{r} \right] = 4.19 \times 10^{-4} \cdot \frac{m}{S} \cdot \left[ \frac{\nu}{r} \right]$  milligal (6 A)

Effect on 
$$A_m$$
 of  $h: \frac{2 \pi k^2 m}{S} \left[ \frac{hl}{r^2} \cos \alpha \right] = 4.19 \times 10^{-4} \cdot \frac{m}{S} \cdot \left[ \frac{hl}{r^2} \cos \alpha \right]$  milligal (6 B)

These formulas can easily be deduced by considering the change of the flux of lines of force through the surface because of the displacements v and h. In the formulas,  $\alpha$  is the angle between an arbitrary direction in the plane A B and the direction of h, and r is the distance from m to an arbitrary point of the boundary.  $\left\lceil \frac{v}{r} \right\rceil$  and  $\left\lceil \frac{h \, l}{r^2} \right\rceil \cos \alpha$  represent the means of the

quantities  $\frac{v}{r}$  and  $\frac{hl}{r^2}\cos a$  for all directions a. These quantities are both small, because v and l are supposed to be small with regard to r, but the mean of the second one is still smaller than the mean of the first one because of the variable sign of the factor  $\cos a$ .

The smallness of both effects allows the conclusion that changes of position of the masses only very slightly affect the mean anomaly  $A_m$  and so we may approximately say that  $A_m$  is independent of those positions. This leads to the above rule.

A second conclusion is that horizontal displacements have still less effect than vertical displacements of the masses. We can apply this conclusion to get an idea about the effect on the mean anomaly of changes of the system of isostatic reduction. When we change over, for instance, from local to regional compensation without changing the depths of the compensating masses, the mean anomaly will not appreciably vary, but if we change over to another depth of compensation, a slight variation may occur.

To get a better idea of the amount of this variation, we shall take an example with extreme figures. Let us consider the change of the mean anomaly over an area of some 5000 km diameter in an ocean of 5000 meters depth, when we apply an isostatic reduction that removes the topographic mass-defects of the ocean-water to a depth of 50 km. For these figures formula 6 A gives a variation of  $A_m$  of only 7 milligal. Incase the removal of the masses finds place over less elevation, the effect is correspondingly smaller. So we find our conclusion confirmed regarding the smallness of the effect of mass-movements on the mean anomaly. In this computation the effect on  $A_m$  of masses in other parts of the Earth has been neglected.

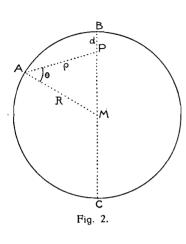
We return to the main problem of determining the distribution of the anomalous masses when the field of gravity anomalies is known. It has been mentioned at length that an absolute solution of this problem cannot be found; usually an infinite number of solutions is possible. In these circumstances the method of investigation will consist in trying different mass-distributions that are suggested by other considerations and comparing their field of attraction to the field that is known. Eventually we shall have to alter the dimensions of the solution in order to adapt it as well as possible. In this way we shall try to find out whether the system of mass-distribution is possible or not.

The method may also be put in this way that we compute the effect on the gravity of the taking away of this system of masses. If, in doing this, we keep the station on the geoid, it is not sufficient to compute the direct attraction of the masses in the station, but it must likewise be taken into account that the removal of the masses alters the geoid and that, thus, the station has to be shifted. In this way, the masses have a secondary effect on the gravity in the station. This indirect effect is the free-air reduction corresponding to the removal of the station from the original geoid to the new geoid.

If we succeed in finding a system of masses of which the combined direct and indirect effects produce the anomalies as they have been found, this solution fulfills the requirement, mentioned in the beginning of this § of taking into account the indirect part of the anomalies caused by the deviation between the gooid and the ellipsoid.

For giving an idea about the magnitude of the indirect effect of a system of masses with regard to the direct effect, a simple case will be considered, viz. a concentrated mass in an arbitrary position in the Earth. Let m be the mass, situated in the point P at a depth d below the geoid,

If  $\varrho$  is the distance from P of an arbitrary point A of the geoid and  $\theta$  the angle between the radius of A and the line AP, the direct effect of the mass m on the gravity in A is the vertical component of the attraction in A of the mass m, i.e.



$$d_1g = k^2 m \frac{\cos \theta}{\varrho^2}$$

or, by eliminating  $\theta$ 

$$d_1g = k^2 m \frac{\varrho^2 + 2 Rd - d^2}{2 R \varrho^3}$$
 (7)

in which R is the mean radius of the Earth and  $k^2$  the Newtonian gravitation constant.

The indirect effect of m is brought about by the alteration of the geoid caused by m. In a point of the geoid it is shifted over a distance E/g, if E represents the potential in this point caused by m. So in A it is shifted outwards over a distance

$$h = \frac{k^2 m}{\varrho g}$$

The corresponding free-air reduction over this distance gives the indirect effect of m in A and so we find

$$d_2g = -\frac{2gh}{R} = -2k^2 \frac{m}{\rho R}$$
 (8)

The total effect of m in A is

$$dg = d_1g + d_2g = k^2 m \frac{(2R - d) d - 3 \varrho^2}{2R \rho^3}$$
 (9)

Examining the formulas 7 and 8 we see that the indirect effect has the opposite sign to the direct effect and this confirms the conclusion arrived at in the previous part of this chapter, that in neglecting the indirect part of the anomalies, the direct or attractional part is underestimated.

We see further that both effects diminish for increasing distances  $\varrho$ , but the indirect effect decreases less quickly. This is clearly illustrated by the values of those effects for the points B and C, B being the nearest point of the geoid to P and C the farthest. We find

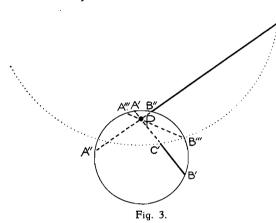
	$d_1g$	$d_2g$
For B	$\frac{-k^2m}{d^2}$	$-\frac{2 k^2 m}{Rd}$
For C	$\frac{k^2 m}{(2 R - d)^2}$	$\frac{2 k^2 m}{R (2 R - d)}$

The ratio of  $d_1g$  to  $d_2g$  is -R/2d for the point B and -R/2(2R-d) for the point C. So, supposing d to be small with regard to R, this ratio is large for B and it is only  $-\frac{1}{4}$  for C.

We may conclude that the indirect effect is only a small part of the total effect for points close to the mass, but the ratio is increasing quickly with the distance. For

$$\varrho = \frac{1}{3} \sqrt{3 d} (2R - d)$$

the indirect effect is already entirely neutralizing the direct effect, i.e. the total for this point is zero (form. 9). For greater distances the indirect effect predominates and the sign of the total effect is reversed; for the point C it attains a negative value that is nearly three times the value in this point of the direct effect alone.



A good idea of the ratio of the direct and indirect effects is given by fig. 3. The circle A' A'' B' B'' represents a cross-section of the Earth and the circle C' C'' is found by multiplying this circle by — 3 with regard to the point P as origin. From the formulas 7 and 9 we deduce easily the following formulas for the direct and for the total effect for the point A'

$$d_1g = \frac{k^2 m}{2 R \varrho^2} \times A' B'$$
$$dg = \frac{k^2 m}{2 R \varrho^2} \times C' B'$$

So the figure allows a quick estimate of the relative values of the direct and the total effects; they are proportional to the chord A'B' and the section C'B' between both circles. For a point A'' the distance C''B'' has to be taken with negative sign. For the point A''' the total effect is zero and so this is the point, mentioned above, where the indirect effect neutralizes the direct effect.

The deduction of the direct and of the indirect effects for more complicated mass-distributions is usually a rather tedious affair. Generally the equations are difficult to handle and the computations are laborious. In the well-known systems of isostatic reduction, to be discussed in § 5 of this chapter, we have methods for doing this in a relatively simple way for special mass-distributions that depend in a given way on the topography. Another contribution to this subject is given in the next paragraphs; it may come in useful for simplifying the computations in two other cases of mass-distributions, i.e. in plane distributions and in axially symmetric distributions. Their dimensions as well as the distances to the station where the attraction is to be determined are assumed to be small enough for allowing to neglect the curvature of the Earth; in this case the indirect effect is likewise negligible and so only the direct effect is treated of.

In the subsequent paragraphs of this chapter we shall consecutively discuss the reduction of the gravity values from the station to the geoid by means of the free-air reduction, the taking away of the attraction of the topographic features by means of a modified Bouguer reduction and the different systems of isostatic reductions. All these reductions have to be

supplied with indirect reductions for taking into account the corresponding alterations of the geoid.

Up to now, the attention has been concentrated on the problem of finding the masses that cause the anomalies. We may call this the geometrical interpretation of the anomalies, because it is the geometrical distribution of the masses that is the object of the research. The results are important for the investigation of the geological history of the Earth's crust because the causes of the mass-irregularities are related to this history; this will be clearly demonstrated by the discussion of the gravity results in the East Indies.

We shall now consider the physical interpretation of the anomalies and ask whether it is possible to draw conclusions from the anomalies about the forces and stresses that are working in the Earth. The principle of isostasy is the base for these considerations; we shall, therefore, adopt this principle in its physical meaning as the hydrostatic equilibrium of the Earth's crust on the plastic layer. According to this conception, isostasy means the absence of forces and stresses, except the smaller local stresses in the crust brought about by the weight of its inner and outer irregularities. Deviations of isostasy, on the contrary, presume the presence of forces and stresses. Although it is easy to see that it is impossible to come to exact results regarding their magnitude and direction, we can arrive at valuable suppositions when we use them in connection with the data from other sides, from geology and seismology. A possible supposition for explaining extensive fields of positieve anomalies is e.g. the presence of lateral compression in the Earth's crust. Another supposition looks for their cause in the action of the substratum.

We shall discuss these physical considerations in § 5 about isostatic reduction, in § 8 which contains a discussion of the results for the Earth's crust and for the gravity field of lateral compression of the crust, and in § 9, which gives a short discussion of the effect of phenomena in the substratum, especially of convection-currents.

§ 2. Formulas and Tables for computing the attraction of plane mass-distribution and axially symmetric mass-distributions.

#### A. A plane mass-distribution.

We assume a plane mass-distribution, extending horizontally over a great distance in one direction and having the same cross-section in all planes perpendicular to it. We further assume that the dimensions of the cross-section are so small that the curvature of the Earth may be neglected, i.e. not more than a few hundreds of kilometers. It can be proved that in this case the indirect effect of this mass-distribution in stations at dictances not exceeding the same order of magnitude is of the order of d/R times the direct effect, d being the depth of the masses and R the Earth's radius. This indirect effect will be neglected and so we shall only determine the direct attraction of the masses.

We start from the case of a rectangular cross-section of a breadth x and a height y and  $\chi$  we compute the vertical component  $P_0$  of the attraction in the left-hand upper corner O. Assuming the density to be  $\varrho$ , we find

$$P_0 = 2 k^2 \varrho \left[ y bg tg \frac{x}{y} + \frac{1}{2} x lg \left( 1 + \frac{y^2}{x^2} \right) \right]$$
 (7)

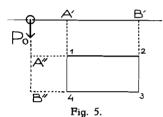
We can write this formula as the product of the density, of the height y and of a function F of the ratio x/y = p

$$P_0 = \varrho \ y \ F$$
  $F = 2 \ k^2 \ \left[ \ bg \ tg \ p + \frac{1}{2} \ p \ lg \left( 1 + \frac{1}{p^2} \right) \right]$  (8)

It follows that F(-p) = -F(p)

The function F has been tabulated and so it is easy to compute the attraction  $P_0$ ; we determine p, look up F in the table and multiply it with  $\varrho$  y.

If the point O, where we wish to know the component of the attraction  $P_0$ , is situated otherwise with regard to the rectangle, we can compute it by determining  $P_0$  for the rectangles OA'1A'', OB'2A'', OB'3B'' and OA'4B'', and by adding them together with alterting sign.



$$\begin{array}{l} P_0 = \varrho \; (y_1 \, F_1 - y_2 \, F_2 + y_3 \, F_3 - y_4 \, F_4) \\ (y_1 = y_2 \, \text{and} \, y_3 = y_4) \end{array}$$

If part of the rectangle is on the other side of the vertical through O, this formula remains valid if we realize that p and consequently F have negative sign for the corners on that side.

For an arbitrary cross-section, we can find an approximate value for  $P_0$  by representing the cross-section by a rectangularly blocked line, by computing  $P_0$  for all the rectangles determined by O and the corners  $1, 2, 3, \ldots n$ , and by adding them together with alternating sign.

$$P_{0} = \varrho \ (y_{1} F_{1} - y_{2} F_{2} + y_{3} F_{3} - y_{4} F_{4} + \dots)$$

$$(y_{1} = y_{2}, y_{3} = y_{4}, \text{ etc.})$$
(9)

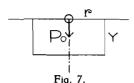
For the sign of the product y F for a certain corner, we may express the following rule resulting from the above deduction. Connecting the corner with O, the sign of the product is positive when the acute angle between this line or its prolongation and the horizontal or vertical boundary of the cross-section at this corner lies inside the cross-section.

Table for F plane mass-distributions.

р	0	1	2	3	4	5	6	7	8	9
0.0	0.00	0.75	1.31	1.80	2.25	2 66	3.05	3 42	3,76	4.09
0.1	4.41	4.71	5.00	5.28	5.55	5.81	6.06	6 30	6.53	6.76
0.2	6.98	7.19	7.40	7.60	7.80	7.99	8.18	8.36	8.54	8.71
0.3	8.88	9.04	9.20	9.36	9.51	9.66	9.81	9.95	10.09	10.23
0.4	10 36	10.49	10.62	10.74	10.87	10.99	11.10	11.22	11.33	11.44
0.5	11.55	11.66	11.77	11.87	11.97	12.07	12.16	12.26	12.35	12.44
0.6	12.53	12.62	12.70	12.79	12.87	12.95	13.03	13.11	13.19	13.26
0.7	13.34	13.41	13.49	13.56	13.63	13.70	13.76	13.83	13.90	13.96
0.8	14.02	14.08	14.15	14.21	14.27	14.32	14.38	14.44	14.49	14.55
0,9	14.60	14.66	14.71	14.76	14.81	14.86	14.91	14.96	15.01	15.05
1.0	15.10	15.15	15.19	15.24	15.28	15.32	15.37	15 41	15.45	15.49
1.1	15.53	15.57	15.61	15.65	15.69	15.73	15.76	15.80	15.84	15.87
1.2	15.91	15.94	15.98	16.01	16.05	16.08	16.11	16 14	16.18	16.21
1.3	16.24	16.27	16.30	16.33	16.36	16.39	16.42	16.45	16.47	16.50
1.4	16.53	16.56	16.58	16.61	16.64	16.66	16.69	16.71	16.74	16.76
1.5	16.79	16 81	16 84	16.86	16.89	16.91	16.93	16 95	16.98	17.00
1.6	17.02	17.04	17.06	17.09	17.11	17.13	17.15	17.17	17.19	17 21
1.7	17.23	17.25	17 27	17.29	17.31	17.33	17.35	17.36	17.38	17.40
1.8	17.42	17.44	17.45	17.47	17.49	17.51	17.52	17.54	17.56	17.57
1.9	17.59	17.61	17.62	17.64	17.65	17.67	17.68	17 70	17.72	17.73
2.0	17.75	17.76	17.77	17.79	17.80	17.82	17.83	17 85	17.86	17.87
2.1	17.89	17.90	17.92	17 93	17.94	17.96	17.97	17.98	17.99	18.01
2.2	18.02	18 03	18.04	18.06	18.07	18.08	18.09	18.10	18.12	18.13
2.3	18.14	18.15	18.16	18.17	18.18	18.20	18.21	18 22	18.23	18.24
2.4	18.25	18.26	18.27	18.28	18.29	18.30	18.31	18.32	18.33	18.34
2 5	18.35	18.36	18.37	18.38	18.39	18.40	18.41	18.42	18.43	18.44
2.6	18.45	18.46	18.47	18.48	18.48	18.49	18.50	18.51	18.52	18.53
2.7	18.54	18.55	18.55	18.56	18.57	18.58	18.59	18.60	18.60	18.61
2.8	18.62	18.63	18.64	18.64	18.65	18.66	18.67	18.67	18.68	18,69
2.9	18.70	18.71	18.71	18.72	18.73	18.73	18.74	18.75	18.76	18.76
3.0	18.77	18.78	18.78	18.79	18.80	18.80	18.81	18.82	18.82	18.83
3.1	18.84	18.84	18.85	18.86	18.86	18.87	18,88	18.88	18.89	18.90
3.2	18.90	18.91	18.91	18.92	18.93	18,93	18.94	18.94	18.95	18.96
3.3	18.96	18.97	18.97	18.98	18.99	18.99	19.00	19.00	19.01	19.01
3.4	19.02	19.02	19.03	19.03	19.04	19.05	19.05	19.06	19.06	19.07
3.5	19.07	19.08	19.08	19.09	19.09	19.10	19.10	19.11	19,11	19.12
3.6	19.12	19.13	19.13	19.1 <del>4</del>	19.14	19.15	19.15	19.16	19.16	19.17
3.7	19.17	19.18	19.18	19.19	19.19	19.20	19.20	19.20	19.21	19.21
3.8	19.22	19.22	19.23	19.23	19.24	19.24	19.24	19.25	19.25	19.26
3.9	19.26	19.27	19.27	19.27	19.28	19.28	19.29	19.29	19.30	19.30
4.0	19.30	19.31	19.31	19.32	19.32	19.32	19.33	19.33	19.34	19.34
4.1	19.34	19.35	19.35	19.35	19.36	19.36	19.37	19.37	19.37	19.38
4.2	19.38	19.38	19.39	19.39	19.40	19.40	19.40	19.41	19.41	19.41
4.3	19.42	19.42	19.42	19.43	19.43	19.43	19.44	19.44	19.44	19.45
4.4	19.45	19.45	19.46	19.46	19.46	19.47	19.47	19.47	19.48	19.48
4 5	19.48	19.49	19.49	19 49	19.50	19.50	19.50	19.51	19.51	19,51
4.6	19.52	19.52	19.52	19.52	19.53	19.53	19.53	19.5 <del>1</del>	19.54	19.54
4 7	19.55	19.55	19.55	19.55	19.56	19.56	19.56	19.57	19.57	19.57
4.8	19.58	19.58	19.58	19.58	19.59	19.59	19.59	19.59	19.60	19.60
4.9	19.60	19.60	19.61	19.61	19.61	19 62	19.62	19.62	19.62	19.63
5.0 \\ 0.2 \\ 0.1 \\ 0.0	19.63 20.29 20.95	20.22 20.89	20.16 20.82	20.09 20.75	20.02 20.69	19.96 20.62	19.89 20.55	19 83 20 49	19.76 20.42	19.69 20.36
$\frac{1}{p}$	0	1	2	3	4	5	6	7	. 8	9

#### B. An axially symmetric mass-distribution.

We assume that the axis, round which the distribution is symmetric, is vertical, and that we only wish to know the attraction in this axis. About the dimensions the same assumptions are made as for the previous case and in the same way only the direct effect will be taken into account.



We shall follow the same method as above. Starting from the case of a cylinder of a radius r and a height y, we find the attraction  $P_0$  in the center of the upper surface by means of the formula

$$P_0 = 2 k^2 \varrho (r + y - \sqrt{r^2 + y^2}) \tag{10}$$

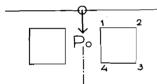
We can write this again as the product of the density, of the height y and of a function G of the ratio r/y = p.

$$P_0 = \varrho \, \eta \, G$$
  $G = 2 \, k^2 \, \varrho \, (p + 1 - \sqrt{p^2 + 1})$  (11)

We find again that G(-p) = -G(p).

The function G and its logarithm have been tabulated on the next page and so we get the same simple computation for  $P_0$ .

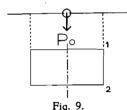
For a rectangular cross-section in another position with regard to O, we find in the same way as for the previous case



$$P_0 = \varrho (y_1 G_1 - y_2 G_2 + y_3 G_3 - y_4 G_4)$$
  
 $(y_1 = y_2 \text{ and } y_3 = y_4)$ 

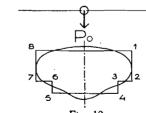
Fig. 8.

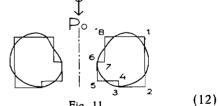
If O lies in the axis of the rectangle, the formula is simpler because the first and the last term are zero.



$$P_0 = \varrho \ (-y_1 G_1 + y_2 G_2).$$

For an arbitrary cross-section, we can find again an approximation by representing it by a rectangularly blocked line. For the two cases of the figures we have





 $P_0 = \varrho \left( -y_1 G_1 + y_2 G_2 - y_3 G_3 + y_4 G_4 \right)$   $P_0 = \varrho \left( -y_1 G_1 + y_2 G_2 + \dots + y_8 G_8 \right)$ 

Table for G axially symmetrical mass-distributions.

р	0	1	2	3	4	5	6	7	8	9
0.0	0.00	0.42	0.83	1.24	1.64	2.04	2.44	2.83	3.22	3.60
0.1	3.98	4.36	4.73	5.10	5.46	5.82	6.17	6.52	6.87	7.21
0.2	7.55	7.89	8.22	8.55	8.87	9.19	9.50	9.81	10.12	10.43
0.3	10.73	11.03	11.32	11.61	11.89	12.18	12.45	12.73	13.00	13.27
0.4	13.54	13.80	14.06	14.31	14.56	14.81	15.06	15.30	15.54	15.77
0.5	16.01	16.24	16.47	16.69	16.91	17.13	17.35	17.56	17.77	17.98
0.6	18.18	18.38	18.58	18.78	18.97	19.16	19.35	19.54	19.73	19.91
0.7	20.09	20.27	20.44	20.62	20.79	20.95	21.12	21.29	21.45	21.61
0.8	21.77	21.92	22.08	22.23	22.38	22.53	22.68	22.82	22.96	23.10
0.9	23.24	23.38	23.52	23.65	23.78	23.92	24.05	24.17	24.30	24.42
1.0	24.55	24.67	24.79	24.91	25.03	25.15	25.26	25.38	25.49	25.60
1.1	25.71	25.82	25.92	26.03	26.13	26.24	26.34	26.44	26.54	26.64
1.2	26.73	26.83	26.93	27.02	27.12	27.21	27.30	27.39	27.48	27.57
1.3	27.66	27.74	27.83	27.91	28.00	28.08	28.16	28.24	28.32	28.40
1.4	28.48	28.56	28.63	28.71	28.78	28.86	28.93	29.01	29.08	29.15
1.5	29.22	29.29	29.36	29.43	29.50	29.56	29.63	29.70	29.76	29.83
1.6	29.89	29.95	30.01	30.08	30.14	30.20	30.26	30.32	30.38	30.44
1.7	30.50	30.55	30.61	30.67	30.72	30.78	30.84	30.89	30.95	31.00
1.8	31.05	31.10	31.16	31.21	31.26	31.31	31.36	31.41	31.46	31.51
1.9	31.55	31.60	31.65	31.70	31.74	31.79	31.84	31.88	31.93	31.97
2.0	32.02	32.06	32.10	32.14	32.19	32.23	32.27	32.32	32.36	32.40
2.1	32.44	32.48	32.52	32.56	32.60	32.64	32.68	32.72	32.76	32.79
2.2	32.83	32.87	32.91	32.94	32.98	33.02	33.05	33.09	33.12	33.16
2.3	33.20	33.23	33.26	33.30	33.33	33.36	33.39	33.43	33.46	33.49
2.4	33.52	33.56	33.59	33.62	33.66	33.69	33.72	33.75	33.78	33.81
2.5	33.84	33.87	33.90	33.93	33.95	33.98	34.01	34.04	34.07	34.10
2.6	34.13	34.16	34.19	34.21	34.24	34.26	34.29	34.32	34.34	34.37
2.7	34.40	34.42	34.45	34.47	34.50	34.52	34.55	34.58	34.60	34.63
2.8	34.65	34.68	34.70	34.72	34.75	34.77	34.79	34.82	34.84	34.86
2.9	34.88	34.91	34.93	34.95	34.98	35.00	35.02	35.04	35.06	35.08
3.0	35.11	35.13	35.15	35.17	35.20	35.22	35.24	35.26	35.28	35.30
3.1	35.32	35.34	35.36	35.38	35.40	35.42	35.44	35.46	35.48	35.50
3.2	35.51	35.53	35.55	35.57	35.59	35.61	35.63	35.64	35.66	35.68
3.3	35.70	35.72	35.73	35.75	35.77	35.79	35.80	35.82	35.84	35.86
3.4	35.87	35.89	35.91	35.92	35.94	35.96	35.98	35.99	36.01	36.03
3.5	36.04	36.05	36.07	36.09	36.10	36.12	36.13	36.15	36.16	36.18
3.6	36.20	36.21	36.23	36.24	36.26	36.27	36.28	36.30	36.31	36.33
3.7	36.35	36.36	36.38	36.39	36.41	36.42	36.43	36.45	36.46	36.48
3.8	36.49	36.50	36.52	36.53	36.54	36.55	36.57	36.58	36.60	36.61
3.9	36.62	36.64	36.65	36.66	36.68	36.69	36.70	36.71	36.72	36.74
4.0	36.75	36.77	36.78	36.79	36.80	36.81	36.82	36.84	36.85	36.86
4.1	36.87	36.88	36.90	36.91	36.92	36.93	36.94	36.95	36.97	36.98
4.2	36.99	37.00	37.01	37.02	37.03	37.04	37.06	37.07	37.08	37.09
4.3	37.10	37.11	37.12	37.13	37.14	37.15	37.17	37.18	37.19	37.20
4.4	37.21	37.22	37.23	37.24	37.25	37.26	37.27	37.28	37.29	37.30
4.5	37.31	37.32	37.33	37.34	37.35	37.36	37.37	37.38	37.39	37.40
4.6	37.41	37.42	37.43	37.43	37.44	37.45	37.46	37.47	37.48	37.49
4.7	37.50	37.51	37.52	37.53	37.54	37.55	37.56	37.57	37.58	37.58
4.8	37.59	37.60	37.61	37.62	37.63	37.64	37.64	37.65	37.66	37.67
4.9	37.68	37.68	37.69	37.70	37.71	37.72	37.73	37.73	37.74	37.75
5.0 ( 0.2 ( 0.1 0.0	37.76 39.82 41.91	39.61 41.70	39.40 41.49	39.20 41.28	38.99 41.07	38.78 40.86	38.58 40.65	38.37 40.44	38.17 40.23	37.96 40.03
$\frac{1}{p}$	0	1	2	3	4	5	6	7	8	9

We get the same rule as in the previous case for the sign of the different terms of 12; we have to give positive sign to the product for those corners, where the acute angle between the horizontal or vertical boundary of the cross-section and the line connecting the corner with O or its prolongation, is inside the cross-section.

#### § 3. Reduction of gravity values from the station to the geoid.

This is done by applying the free-air reduction.

$$\delta_{g}$$
  $=$   $+$   $\frac{2g}{R}$   $h$   $=$   $+$  0.3083  $h$   $mgal$ 

in which h is the elevation in meters of the station above sea-level. This formula represents the increase of attraction exerted by the total mass of the Earth when we get nearer to the center of the Earth by an amount of h meters. The reduction leaves the attraction by the topography unaltered.

For the sea-observations made at the surface of the sea, this reduction is zero and for observations made in submarines, at depths of thirty meters or less, it is small but negative corresponding to the negative value of h. In this last case we have to apply also another correction that takes account of the fact that the removal of the station from a certain depth d to the surface of the sea, changes the sign of the attraction by the layer of water above the station. This correction is given by

$$\delta'_g = +4 \pi \varrho_s k^2 d = +0.086 d$$
 mgal.  $(\varrho_s = \text{density sea-water}).$ 

The correction is still smaller than the other; it never amounts to more than a few milligal.

The gravity observations at sea have been subjected to both corrections before their publication in Part I of this report. We have found in this way the values, that would have been observed if the observations had been made at the surface of the sea. The anomalies thus obtained are still affected by the topography of the sea-bottom and so they may be put on the same line with the free-air anomalies on land. It seems indicated to call them likewise free-air anomalies.

There is, however, an important difference from the free-air anomalies on land because they are affected by the topography as it really is and this is not the case for those on land. The fact that the observations on land have not been corrected for the topography, does not mean that the topography has not been altered. It is clear that, in order to leave its effect on the station as it was before the station was moved downwards over h meters, it is necessary to remove the topography likewise over this distance.

This is a complicated conception and so it is usually replaced by another alteration of the topography that gives roughly the same effect on the station. It is usually imagined that the topography above sea-level is moved downwards in its own vertical till it is condensed in an infinitely thin layer, just inside the geoid. This layer gives approximately the same attraction at the station in its new position on the geoid, as the original topography gave in the original position of the station. So, approximately, this mass-condensation likewise leaves unaltered the effect of the topography. For a regular topography with nearly constant elevation, this

approximation is a good one, but for irregular topography with strong variations in elevation, this is no longer the case. So in this case the mass-condensation implies the application of a further reduction that is usually indicated by its german name: "Gelände Reduktion" 1).

As the mass-removals in both cases are limited to a few kilometers, the corresponding alteration of the geoid is small. It does not exceed a few meters and so we may neglect it in connection with the problem of the Figure of the Earth and we may likewise neglect the small indirect part of the free-air reduction that corresponds to this small alteration of the geoid.

The question arises whether the free-air anomalies can be used for determining the figure of the Earth by means of the theorem of Stokes. The anomalies at sea are certainly suitable for this purpose. The observations have been made on the geoid or so near to the geoid that the small reduction to the geoid practically cannot give rise to any uncertainty and the second condition that all the masses of the Earth have to be inside the geoid, is likewise fulfilled at sea.

The free-air anomalies on land are also reduced to the geoid and if we adhere to the conception of the condensation of the topographic masses to an infinetely thin layer inside the geoid, the second condition about all the masses being inside the geoid, is likewise fulfilled. For gravity results in an area of irregular topography, however, this last conception makes it necessary to apply a further reduction, the "Gelände Reduktion". Otherwise masses would be left outside the geoid.

It may be concluded that the free-air anomalies, on land eventually corrected by the "Gelände Reduktion" in areas with irregular topography, can be used for the determination of the figure of the Earth by means of the theorem of Stokes. They have the advantage of giving the actual geoid without appreciable modification, but the field of anomalies is irregular because of its being affected by all the effects of topography and compensation. This is a disadvantage as the number of gravity results is limited and in these circumstances each value is only representative for a small area.

For the investigation of the Earth's crust, the field of free-air anomalies is neither suitable at sea nor on land, because the effects of eventual anomalous masses in the crust are hidden by the strong and irregular fields of attraction caused by the topographic masses. So we have to take off these effects before we can conclude anything, and this leads to the application of the modified Bouguer reduction of the next paragraph.

#### § 4. The modified Bouguer Reduction or Topographic Reduction.

This reduction takes away the effect of the topographic masses on the gravity of the station. For land-stations the topographic masses are the masses between the surface and the geoid. So the principal part of this reduction is the Bouguer reduction which takes off the attraction of an infinite layer of mean crust's density and a thickness equal to the elevation of the station above the geoid. We have to apply two modifications to this reduction and this gave rise to call this topographic reduction a modified Bouguer reduction; firstly we have to take into account the deviation of the real topography from the upper surface of this layer and secondly we have to decide up to which distance we wish to take away the topography and we have to limit the layer

<sup>1)</sup> A good exposition of this and other questions of reduction is found in: "The Reduction of Observed values of Gravity to Sea level", by WALTER D. LAMBERT, Bulletin Géodésique No. 26, 1930.

correspondingly. We may conform to both requirements by supplementing the Bouguer reduction with a "Gelände Reduktion" and with a correction for limiting the layer to the required dimensions or we may do it by computing the effect of the topographic masses by means of a zone method like the Hayford-Bowie method for isostatic reduction.

For taking away the effect of the topography at sea-stations, we have to add the attraction of a system of masses, confined between sea-level and the sea-bottom and having a density equal to the difference of the mean density of the crust and of sea-water. In other words, we imagine the sea filled up with masses till it has the same density as the continental crust. Here again we must decide up to which distance we wish to do this. For the reduction of the observations at sea, this distance has been chosen at 166 km, i.e. the taking away of the effect of the topography has been done for the zones A—O of the Hayford-Bowie system.

The anomalies obtained by this reduction are not suitable for the determination of the Figure of the Earth by means of the theorem of Stokes, because the taking away of so much mass has a considerable effect on the geoid. This complicates the deductions and over and above that it again brings masses outside the geoid and so we should have to apply the reduction for a second time. Another reason for their not being suitable is the fact that this field of anomalies is still strongly variable because of the effect of the isostatic compensation, and so we need a large amount of gravity data for getting a good representation of the field.

The value of this field of anomalies lies in the fact that it gives a complete representation of all the anomalous masses in the upper layers of the Earth. It may be used for studying isostasy, as it demonstrates clearly the effect of the compensating masses and so in many instances it may serve for getting an idea of the way in which the compensation is realized. This is not always the case because it often occurs that the field of the compensating masses is covered over by strong anomalies of another origin. For all precise studies of isostasy, we have to try different systems that appear to be likely and this leads to the application of one or more of the systems of isostatic reduction discussed in the next paragraph. Another reason why exact conclusions from this field are difficult, is the great shift of the geoid that corresponds to it and which ought to be taken into account by a secondary reduction of the gravity results to this new geoid. This point would give rise to further computations.

In order to make these modified Bouguer anomalies better representative of the anomalous masses in the area of the station, the gravity results of this publication have been freed, as well as possible, from the effect of anomalous masses in other parts of the Earth, by correcting them for the complete topography and compensation of all the numbered zones of the Hayford-Bowie system. This way of doing presumes that, roughly speaking, isostasy is valid for most parts of the Earth. This assumption seems reasonable because all the present data point towards the truth of it. The modified Bouguer reduction as it has been applied to the gravity data of this publication has, therefore, consisted of a topographic reduction for the zones A—O and an isostatic reduction — according to the regional system — of the zones 18—1.

#### § 5. The Isostatic Reduction and the interpretation of the Isostatic Anomalies.

Isostasy, i.e. the principle that topographic masses are compensated by masses in the crust, is nowadays well recognized, thanks to the pioneer work of the Indian Survey and Airy, Pratt and Dutton and the important researches on this subject of Hayford, Bowie, Heiskanen and others. It has become the base for all gravity interpretation.

The object of an isostatic reduction is to try a certain distribution of the compensating masses according to a given hypothesis about isostasy and to determine the difference of the actual field of attraction — after free-air reduction and topographic reduction — and the field caused by this mass-distribution. The difference is the isostatic anomaly according to this hypothesis. The isostatic anomalies give data, firstly about the way in which the actual compensating masses differ from the assumed masses and secondly about other anomalous masses that eventually occur in the crust. In connection with geological and geophysical considerations, this may lead to important conclusions about the phenomena in the Earth.

We shall base our discussions on the physical interpretation of isostasy, which assumes that it is brought about by the hydrostatic equilibrium of the non-plastic crust on the plastic simalayer. We need not decide here whether the transition of non-plasticity to plasticity is sudden or not, or whether the crust exists of more than one layer; in principle these questions don't affect the considerations. We assume for pure isostasy, that vertical cross-sections of the crust are not subject to stresses having a resultant in horizontal direction. This assumption is needed because of the curvature of the Earth, which brings about that such a force would affect the isostatic equilibrium.

From the physical view-point, the isostatic anomalies consist of two parts, one part being caused by eventual deviations of the actual distribution of the compensating masses from the distribution assumed for the isostatic reduction, and the other brought about by deviations from the isostatic equilibrium.

The first part can never give a mean anomaly of some amount over an extensive area because, according to the rule expressed on page 19, the mean anomaly only depends on the total amount of anomalous masses in the area and this total is approximately zero incase of isostatic equilibrium, independently of the way the compensating masses are distributed. A mean anomaly of some amount thus points to an excess or a defect of mass, i.e. a disturbance of the isostatic equilibrium. The dimensions of the area, that are supposed to be many times the crust's thickness, prevent assuming that it can be supported by the resistance of the crust at the boundary of the area against shearing and bending. Anomalies of small extent, on the contrary, need not be considered as disturbances of the equilibrium, because they can be explained by masses that are carried by the crust. A physical interpretation of gravity, which has to investigate whether there are deviations from isostatic equilibrium, has therefore only a meaning for extensive areas.

It follows from the above that incase of extensive fields of positive anomalies, there is still one possibility of their being caused by internal stresses in the crust, viz. the possibility of horizontal compression, which, because of the curvature of the Earth, disturbs the isostatic equilibrium. This case will be considered at length in § 8.

If this explanation is to be rejected, we have to assume forces exerted on the crust by the subcrustal layer. According to our views about this layer, these forces must have a viscous character and so they must be related to dynamic processes in this layer. Two cases are possible: The movements have their origin in the lower layers themselves, e.g. by convection-currents in these layers, or they are caused by a change of weight of the crust, e.g. by erosion, sedimentation, iceloads or other agents, and the crust tends to reestablish isostatic equilibrium by vertical movements. A short discussion of these two possibilities will be given in § 9. Lastly § 10 contains a short summary of these different view-points with regard to the interpretation of extensive fields of anomalies of the same sign.

We shall now return to the geometrical interpretation, i.e. the investigation of the

distribution of the masses. The base of these discussions is the view-point that isostasy is the equilibrium of the crust as a floating structure on the plastic sima-layer. It follows that the compensation cannot be purely local, because the crust does not consist of separate vertical prisms that are free to move independently for adjusting their equilibrium. The crust is more or less a whole and so in general the compensation must be regional.

The way in which the compensating masses are distributed, depends on the shape of the crust at its upper and lower surfaces and on the density-distribution in the crust. One of the instances that determine the shape of the crust is its elastical deformation under the effect of eventual loads on the crust and the resulting reaction of the substratum. This reaction has a hydrostatical character, eventually complicated by viscous effects incase of relatively quick acting phenomena.

It is clear that the different factors of the problem are predominantly determined by the geological, the tectonical and the morphological history of the crust. We shall shortly examine a few simplified cases.

If we have a part of the crust, where the topography is modified by sedimentation or erosion, we get displacements of mass that are acting as positive or negative loads on the crust. Considering the crust as an elastic plate floating on a denser substratum, this brings about an elastic deformation as long as the stresses don't exceed the strength-limit of the crust. The deformation gives displacements of mass, and so we get alterations in the distribution of the isostatic compensation. Taking for instance the case of a crustal sinking because of sedimentation and assuming that the crust has the same density everywhere, the alteration is confined to the lower boundary where lighter crustal takes the place of denser subcrustal material. We can easily prove that the total amount of negative compensation resulting from this substitution exactly equals the amount of added mass at the surface of the crust. The compensation is regional, i.e. it is spread over a larger area than the load on the surface. In a vertical sense, it is concentrated at the lower boundary of the crust.

Incase we assume another distribution of the density  $\varrho$  with the depth d, the density of the isostatic compensation at the depth d, brought about by a sinking of the crust over a distance u, is in general

$$\varrho_{d-u}-\varrho_d\tag{13}$$

In reality there is probably a slow increase in density downwards in the crust and a discontinuity at the lower boundary between the sial and the sima. In that case part of the compensation according to this formula is distributed over the thickness of the crust and part is concentrated at the lower boundary. If we assume the crust to consist of two layers of different density, another part occurs at the intermediate boundary. In a horizontal sense, the distribution of the compensation is again determined bij the elastical deformation and the compensation is regional in the same degree as according to the first assumption. The compensation may become more local if the loads on the crust are heavy enough to give rise to shearing of the crust; at those places the deformation of the crust has a local character and the compensation likewise.

The same type of regional compensation as we have here treated of, must occur for other loads on the crust. An instance may perhaps be found in folded mountain-ranges like the Jura, where many geologists assume that the upper layer of the crust is thrust together without the main crust taking part in it. Here again the crust, under the load of the range, will bend until

equilibrium has been readjusted and the compensation will be distributed accordingly. In a vertical sense it will again be found partly in the crust and partly at its lower boundary. It is not sure that this really occurs in the Jura, because it is difficult to conceive how the upper layer of the crust can be thrust together without a corresponding shortening of the other layers. This would mean a gliding of one crustal layer over another and this is perhaps possible for short distances but it appears out of the question for long ones. So, if it is true for the Jura we shall, probably, be right in only admitting the possibility of such structures in the neighbourhood of great crustal folding as e.g. the Jura is near the Alps.

Another instance of the above kind of isostatic compensation is probably given by volcanoes. They represent likewise loads on the crust, which must give rise to a crustal bending until isostasy has been reestablished. The question arises, however, in this case where the ejected masses come from and whether they don 't leave mass-defects that have to be added to the picture as negative loads.

So this way of isostatic adjustment by an elastic deformation of the crust under the load of the topography, must doubtless often occur. It cannot, however, be true everywhere. An important exception is found in great mountain-ranges where the whole crust has been thrust together. If the strength of the crust were negligible, this thrusting together would take place under continuous maintenance of the isostatic equilibrium and the outward protuberance of the surface would be accompanied by a larger inward bulge of the lower boundary of the crust in such a way that it would be a reversed reproduction of the outward protuberance on an enlarged vertical scale, this scale being the ratio of the density of the outer crustal layer to the difference of this density and that of the substratum, i.e. about four or five times.

In reality the crust's strength will oppose the deformation and will modify it considerably, but roughly speaking the above conception will remain true. A downward bulge will be formed, which is larger than the topographic feature at the surface in the ratio that has been mentioned. It is difficult to predict the shape that the phenomenen will assume, but it may reasonably be supposed that the formation of this great downward bulge is the principal feature of the crustal deformation, while the formation of the outward protuberance has a secondary character. If we assume the non-plastic crust to consist of two or more separate layers, the phenomenon will be still more intricate, but in principle the conception remains true. The gravity research in the East and West Indies has given important data about this problem and so we shall come back to it in chapters V and IX.

For the time being, we have no exact and generally accepted knowledge about the deformation and a fixed conclusion about the way in which the isostatic compensation is distributed cannot be drawn. In these circumstances the most logical assumption seems to be to admit the distribution as it was given for the above supposition that the crust remains in local isostatic equilibrium during the process, each topographic feature being compensated by masses in the same vertical.

In a vertical sense, the distribution depends on the density distribution of the original crust in an analogous way as in the previous case. If the crust has the same density over its whole thickness, the entire compensation is concentrated in a root at its lower boundary, but if the density of the crust is increasing downwards, only part of it is found in the root and the other part is distributed over the crust. If we assume that every layer of the crust is compressed to k times its original thickness and if T is the original thickness of the whole crust and p the ratio

of the superficial density to the difference of this density and the density of the substratum, the resulting topographic elevation at the surface is

$$h = \frac{k-1}{p+1} T$$

The depth d of an arbitrary point in the crust is increasing by the amount

$$u = (k-1) d - h$$

or, by eliminating k

$$u = \left[ (p+1) \frac{d}{T} - 1 \right] h \tag{14}$$

If  $\varrho_d$  is the density of the original crust at the depth d and  $\varrho_{d+u}$  at the depth (d+u), the density of the compensation at the depth (d+u) after the deformation is

$$\varrho_d - \varrho_{d+u} \tag{15}$$

This formula gives the distribution of the compensation over the crust; the remaining part is concentrated in the root at its lower boundary. If the crust consists of two layers, part of it is located in a root of the upper layer at the intermediate boundary.

It was already remarked that generally this distribution of the compensation will not be realized because the deformation of the crust is more complicated. The local compensation will certainly be untrue for topographic features that are caused by erosion; for these features a regional compensation like that of the previous part of this paragraph will prevail. So it may be expected that these mountain-ranges show complicated distributions of the compensating masses having partly a local character in the shape of a root at the lower boundary of the crust and partly a regional character corresponding to a bending of the crust.

Another type of crustal movements that differs, partly or entirely, from the case of crustal bending, is the type of the epirogenetical or vertical movements of the crust. So little is known about the causes of these movements that it is difficult to predict how the resulting topographic features are compensated. It may reasonably be supposed that, at least in some cases, these movements are brought about by changes of density in the crust and, in consequence of that, vertical movements for the preservation of isostatic equilibrium. These changes of density might be caused by variations of temperature, by compression or by changes of state of the crustal materials.

This assumption would lead to the assumption of a distribution of the compensation over the layers of which the density has changed. Incase the whole crust should take part in it, this would bring about a type of compensation according to Pratt's hypothesis of isostasy, i.e. a regular distribution of the compensation over the whole crust.

It might be asked whether such changes of density on a great scale are really happening. This question cannot be easily decided, but there is no doubt that there are several indications in this direction. Variations of temperature, e.g., are likely to take place, as has for instance often been pointed out by Bowie. So it seems probable that this kind of isostatic compensation will also occur in the Earth's crust.

The most important feature of the crust, the presence of continents and oceans, has not yet been considered. As nothing is known about their origin, we cannot say much about the

constitution of the Earth's crust in these two cases nor about the way in which the isostatic equilibrium is realized. The only thing that can be said in this regard is, that all the observations at sea have confirmed that it is realized in the oceanic parts; these parts are, roughly speaking, in isostatic equilibrium with the continental parts. The seismological research has given some important indications about the thickness and density of the different crustal layers. They seem to point towards the Airy type of compensation; the non-plastic crust appears to be considerably thicker for the continents than for the oceans. It may be hoped that along this line our knowledge about the constitution of the crust will further increase in the future. A great number of gravity profiles over the continental coasts, where both crustal parts are contiguous, may likewise contribute to give us a better idea about the differences of constitution and about the way in which the compensation is realized. The gravity material of this publication gives already some indications in this regard and so we will come back to this point in chapter IX.

The conclusion of this short consideration of the phenomena of the Earth's crust is, that we cannot expect that all the topographic features are isostatically compensated according to the same system of compensation. It seems impossible to find a system that meets all the cases and so no method of isostatic reduction can be generally applicable. The ideal isostatic reduction should have to apply several systems together, assuming for each topographic feature the type of compensation that is most likely to be true for that case.

Although such a mixed system of isostatic reduction does not appear to be impossible, the practical difficulties are so great that it is questionable whether it will ever be feasible. Until now only uniform methods have been applied that assume the same type of compensation for the entire topography of the Earth. Three methods are available.

The first method is the well-known method of Hayford-Bowie, which is in use in the U. S. Coast and Geodetic Survey. It is based on Pratt's hypothesis of isostasy; the compensation is assumed to be local and to be regularly distributed between the Earth's surface and a surface at a certain depth below it. For this depth of compensation the value of 113.7 km has been assumed. In a simple way it is possible to change over to another depth of compensation; in "Investigations of Gravity and Isostasy", U. S. Coast and Geodetic Survey No 40, 1917, p. 98—99, Bowie has given the factors that are needed for this transformation. As a result of an extensive investigation, based on a large number of gravity stations, Bowie considers a depth of 96 km to be best adapted to the gravity results.

The second method has been given by Heiskanen in the "Bulletin Géodésique" of April 1931. It is based on Airy's hypothesis of isostasy; the compensation is concentrated in roots at the lower boundary of the crust and these roots form an inverse reproduction of the topography on an enlarged vertical scale. The density of the crust being assumed at 2.67 and of the substratum at 3.27, the enlargement scale is 4.45. The tables of Heiskanen are given for normal thicknesses of the crust, corresponding to zero topography, of 40, 60, 80 and 100 Km. This method likewise assumes the compensation to be local.

The third method has been given by the writer in the "Bulletin Géodésique" of January 1931. It is based on the crustal bending hypothesis of isostasy as it has been mentioned in the beginning of this paragraph. The compensation is regional; in a horizontal sense it is distributed proportional to the vertical displacement of the crust under the effect of the loading of the crust by the topography. In a vertical sense the distribution depends on the assumptions about the density in the crust; if this is assumed to be the same over the whole thickness of the crust, the compensation is concentrated at the lower boundary of the crust. For the crust's thickness,

a value of 25 Km has been taken. This seems a low figure compared with the figure of 96 Km of Bowie, but firstly the compensation is supposed to be concentrated entirely or for the greatest part at the lower boundary of the crust and so we must compare with the depth of the center of gravity of the compensation according to Bowie, i.e. with 48 Km, and secondly the compensation is regional and it is easy to see that this diminishes the depth that best satisfies the field of attraction at the surface.

When we consider the three methods, we see that they correspond fairly well to the different possibilities of compensation that have been deduced by examining the crustal phenomena from a theoretical standpoint. So they provide a statisfactory base for the investigations. Applying the methods to the gravity results, three sets of isostatic anomalies are obtained and the study of these sets gives valuable indications, firstly about the type of isostatic reduction of the different topographic features, secondly about the dimensions of that type that are best adapted to the gravity results, and thirdly about eventual other masses in the crust.

### Interpretation of Isostatic Anomalies.

The base for the interpretation of the anomalies is given by the assumption that in a certain area they only depend on the masses of that part of the crust. In admitting this assumption we neglect the effect of anomalous masses in other parts of the Earth's crust and of errors of compensation in those parts, which will certainly occur because no method of reduction can be true everywhere. This neglecting of the effect of distant masses is doubtless admissible if we consider the local irregularities in the field of the anomalies, because it can safely be asserted that masses at a great distance practically cannot bring about such local irregularities of attraction. It is less sure for the regular parts of these fields and so we cannot admit it in this case as more than a first approximation; the indirect effect of distant masses is larger than the direct effect and may easily attain appreciable values. There is no doubt, for instance, that a change of the depth of compensation of remote areas may give a field of slight anomalies of which neither the indirect nor even the direct part is negligible. This field can be easily computed, because the combined effect of the topography and of the compensation of a distant area is proportional to the depth of compensation. In these computations, we may put the depth of compensation for the Hayford-Bowie reduction at 56,85 km, for the Heiskanen reduction at resp. 40, 60, 80 or 100 km and for the regional reduction at 25 km.

About the problems that we come across in connection with the interpretation of the isostatic anomalies, a few remarks may be made. It may be asserted that the regional isostatic anomalies give indications about the presence of roots of the crust. The regional reduction is based on the assumption of a bending crust and so the lower boundary of the crust, according to this assumption, must be supposed to be a smooth surface. So, if the crust has been compressed and a more or less local root of great dimensions has been formed, this root represents a defect of mass with regard to this assumption and it must show its presence by negative anomalies at the surface.

Considering the character of the phenomenon, it may be expected that these roots will usually have a linear or curved course over the surface of the Earth, depending on the compressive forces that have acted in the crust; the formation of an isolated root seems less probable. According to this reasoning, we may expect that the roots will be indicated at the Earth's surface by strips of negative anomalies in the field of regional isostatic anomalies.

We cannot reverse this statement; every strip of negative anomalies in this field is not necessarily caused by a root of the crust. It may be imagined that there can occur other mass-defects in the crust without any root-formation at its lower boundary. Still, the presence of a root is always a possibility in this case.

If the field of regional isostatic anomalies gives indications of the presence of a root, the consideration of the field of Heiskanen anomalies can at once give a decision whether this root is the exact compensation of a topographic feature at the surface. In that case this field shows no anomalies at this spot. If the negative anomalies don't quite disappear by this reduction nor by a repetition of this reduction with other values for the thickness of the crust and for the density of the compensation, the root can obviously not be considered as the direct compensation of a topographic feature. For getting an idea in this case about its dimensions we may use the tables of § 2.

It is not always the method of reduction that reduces the anomalies to the smallest values, which gives the best insight in the origin of the anomalies. It may be that another set of anomalies provides a clearer idea by showing more regular features. In that case there is reason to suppose that the latter method of reduction is nearer to the truth as to its assumptions about the distribution of the compensation than the first one, but that there are other anomalous masses caused by other phenomena in the crust, which complicate the field of attraction. Instances of this kind will be met with when examining the results of this publication.

In general, the localization of other anomalous masses has to choose from four possibilities. In the first place they can occur at the Earth's surface in the shape of topographical features, that are not compensated isostatically. This case may be present when phenomena have so recently taken place, that the viscous resistance of the substratum has not yet allowed the complete reestablishment of isostasy, e.g. recent vertical movements of the crust, heavy erosion or sedimentation, great volcanic eruptions, etc.

In the second place, they can occur in the crust itself, incase the tectonic phenomena have brought about mass-dislocations. An instance may be found when the crust has been down-warped and the trough has been filled in by sedimentary masses that are lighter than the normal crust's density. These masses then represent a mass-defect in the crust. In the same way, up-warping brings heavier masses in higher layers and causes mass-excesses in the crust.

In the third place, they can occur at the lower boundary of the crust and, if the crust consists of two layers of different density, at the lower boundary of the upper layer too. This case occurs likewise when the crust is warping or buckling. If it is down-warping, a root of lighter crustal material projects in the denser substratum and represents in this way a mass-defect. Incase of up-warping, the reverse occurs.

In the last place, they can be looked for in the substratum. It might be possible that density changes take place there by processes as magmatic differentiation, changes of state or others, but, for explaining gravity anomalies, we must assume these processes to have occurred so recently, that the reestablishment of hydrostatic equilibrium has not yet been realized. A noteworthy supposition is also that of thermic convection processes, giving rise to a more or less stationary break of the equilibrium. We shall consider this possibility more closely in § 9.

The first of these cases differs from the subsequent ones by the greater density of the anomalous masses. This is in the first case the superficial crust's density, i.e. 2.0—2.7 while in the other cases the densities of the anomalous masses are the differences of crustal and subcrustal densities, which for the third one may be put at maximally about 0.6 and for the second and last

ones probably at a smaller figure. In the latter three cases, the dimensions of the masses have, therefore, to be considerably larger than in the first case for giving the same gravity effect.

We shall not further enlarge here on these considerations, because we shall come back to these problems in chapter V, where we will study the results and try to find interpretations.

### § 6. The Bowie Reduction or Indirect Isostatic Reduction.

The isostatic reduction may be considered as a modification of the Earth; the topographic masses and the compensation are both taken away. This brings about a modification of the geoid, which must be taken into account by an indirect reduction reducing the gravity values from the original geoid to the new geoid before comparing them with the formula for normal gravity. This reduction is the Bowie Reduction or Indirect Isostatic Reduction.

Many publications have already appeared about this subject by LAMBERT, CASSINIS, HEISKANEN, JUNG and others. The writer wishes to draw the attention to a recent paper of Karl Jung in the "Zeitschrift für Geophysik" (Jahrg. 8, Heft 1/2): "Schwere und Geoid bei Isostasie", which gives a new study of this matter. Jung discusses the modification of the geoid and the corresponding Bowie reduction for the Hayford-Bowie isostatic reduction and he gives indications about these quantities for the Heiskanen reduction. A summary of his principal results follows here.

Jung points out that, incase the application of the method of isostatic reduction is refined by taking into account the shift of the geoid, other smaller effects, that are usually neglected, ought also to be considered. The usual methods assume that the compensating masses are equal to the topographic masses with opposite sign. When we admit the physical definition of isostasy as the hydrostatic equilibrium of the crust, this is no more than an approximation. The increase of gravity and the convergence of the direction of the vertical towards the inside of the Earth, both bring about that the compensating masses are slightly less than the above amount.

By means of spherical harmonics, Jung computes the effect of these alterations of the compensating masses on the isostatic reduction. For positive topography, i.e. topography above sea-level, the usual methods of isostatic reduction give anomalies that are slightly too large, algebraically speaking; for stations at sea, they are slightly too small.

Jung also determines, likewise by means of spherical harmonics, the shift of the geoid and the corresponding Bowie reduction. As a rough approximation, he finds that in the continents the geoid is shifted inwards over 13.6 m pro 1000 m elevation and at sea outwards over 9.0 m pro 1000 m depth. According to these results, the continental gravity values must be increased by 4.2 mgal pro 1000 m elevation for reducing them to the new geoid, and the oceanic ones must be diminished by 2.8 mgal pro 1000 m depth.

The combination of the effects together gives the conclusion that they more or less compensate each other. The total correction that ought to be applied to the isostatic anomalies as given by one of the usual methods of reduction, is limited, according to Jungs results, to small values lying between — 8 mgal in two areas in the northern part of the Eurasiatic continent and + 6 mgal in a part of the South Pacific.

So no serious error is made when the effects are neglected altogether and the error is smaller than if we should only apply the Bowie reduction without taking into account the effect of the increase of gravity and of the convergence of the verticals towards the inside of the Earth. According to this, the Bowie reduction has not been applied to the results of this publication.

### § 7. The Isostatic Anomalies and the Theorem of Stokes.

For determining the Figure of the Earth by means of the Theorem of Stokes, it is necessary that all the masses are inside the geoid. The isostatic anomalies fulfill this condition because they correpond to an Earth, of which all the masses outside the geoid have been taken away. The only point that remains to be discussed in this connection is, whether this is still true when we take into account the shift of the geoid that is brought about by the isostatic reduction. Incase this shift takes place towards the inside of the Earth, the masses between the original geoid and the new geoid are getting outside again.

This layer, however, has a smooth surface and its thickness will not exceed a few tenths of meters. It will certainly be compensated and the layer of compensating masses inside the geoid must also be regular. Because of the regularity of the two layers, we may conclude that the attraction by the outside layer is practically neutralized by that of the compensating layer and so the gravity anomalies will not be affected when we take away both layers. In this way the outside masses of the new geoid may be completely removed without altering the anomalies and so these anomalies are fulfilling the necessary condition for the application of the Theorem of Stokes. The shift of the geoid brought about by this new mass-transformation, is obviously so small, that it may be neglected.

The isostatic anomalies have advantages that make them especially appropriate for the determination of the Figure of the Earth. They show a more regular field than the free-air anomalies, because they have been freed from the capricious effects of the topography and the compensation and so every value is representative for a greater area than a free-air anomaly generally is. It is clear that this is important because of the small number of available gravity values.

A second advantage of the isostatic anomalies is that the substitution of zero anomalies in the Theorem of Stokes for all those regions of the Earth that have not yet been surveyed gravimetrically, is less likely to bring about errors when we substitute isostatic anomalies instead of free-air anomalies, because there is every reason to admit isostasy as the normal condition of the Earth's crust.

A further advantage of the isostatic anomalies has been mentioned by Walter D. Lambert. He points out that the reduction of the gravity value from the station to the geoid by means of the ordinary formula, given by 0.3083 h mgal, is nearer to the truth when we suppose the Earth to be modified according to the method of isostatic reduction, than according to any other method.

Resuming, we may conclude that the isostatic anomalies appear to be preferable for the determination of the Figure of the Earth. It is clear that in this way the geoid is obtained as it is modified by the isostatic reduction. So, for finding the actual geoid, the result has to be corrected accordingly. For an approximation of this correction, the shift of the geoid may be used as it has been determined by Jung by means of spherical harmonics 1) or as it is given by the approximative formula of Lamber 2). More precise computations will be possible when the special tables will be ready, which the U. S. Coast and Geodetic Survey are now engaged in compiling for this purpose.

i) Karl Jung, "Die Bestimmung der Geoidundulationen aus Schweremessungen", Gerl. Beiträge, Bd 29 (1931), S. 29-58.

<sup>2)</sup> WALTER D. LAMBERT, "An approximate rule for the distance between the Geoid and the Spheroid on the Assumption of complete Isostasy", Bull, Géod. No. 26,

# § 8. Results for the Earth's crust and for the Gravity Field of Lateral Compression of the crust.

The geological data about folding and overthrusting leave no doubt that great horizontal stresses do occur in the crust. We don't know whether these stresses work continuously or only for certain geological periods and we neither know whether their distribution is general or whether they occur only in certain parts of the crust. Lastly we are ignorant of whether they work everywhere in all directions in the crust, or whether they work generally in only one direction. Nevertheless the presence of horizontal stresses in the crust cannot be denied and so it seems desirable to investigate this case theoretically and to see what is the effect on the crust and on the gravity field.

We may immediately distinguish between two different kinds of phenomena. First we may get simple compression of the crust, combined with vertical movements of the crust as a whole for the reestablishment of equilibrium, and secondly we may get elastical deformations of the crust in the shape of a wave-formation. Both phenomena may lead to disrupture of the crust when the stresses exceed a critical limit. We shall begin by considering the first case and afterwards investigate the second one and find out in what circumstances it can occur.

### A. Lateral Compression of the Earth's crust without Wave-formation.

We begin by assuming that the crust is subject in one direction to a pressure d pro unit of vertical cross-section and that it is stressless in sections parallel to this direction. A simple consideration of equilibrium can give us the gravity anomaly which we have to expect when equilibrium has been reestablished in the new conditions. A further investigation will be needed for determining the vertical movements of the crust that are necessary for this reestablishment

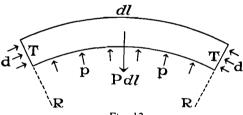


Fig. 12.

of equilibrium; this investigation will have to take into account the changes of density brought about by the compression.

As we assume the crust to be stressless in a sense perpendicular to the main stress-direction, we shall neglect the effect of the curvature of the Earth in that sense. Supposing the crust is in equilibrium in its new condition, we get the following equation

for an element ds of the crust. The dimension perpendicular to the plane of the figure is assumed to be the length-unit, the thickness of the crust T, the Earth's radius R, the weight of the crustal element  $P \, dl$ , and the pressure exerted by the subcrustal layer  $p \, dl$ 

The condition of vertical equilibrium gives

$$P dl - p dl - T d \frac{dl}{R} = 0$$

or, by dividing by dl

$$P - p - \frac{Td}{R} = 0 \tag{16}$$

This equation shows that in this new equilibrium, the crust may weigh Td/R more pro surface-unit than for pure isostatic equilibrium which is given by P = p. This excess of mass causes an attraction at the Earth's surface of

$$A = \frac{2\pi k^2 Td}{R} \tag{17}$$

So this is the isostatic anomaly which will be found if equilibrium has been reestablished.

Incase the crust is subject to a stress d in all horizontal directions, we can follow the same way of investigation and we find twice the effect. The isostatic anomaly in this case is, therefore,

$$A = \frac{4 \pi k^2 Td}{R} \tag{18}$$

By introducing the values for R (6370 km) and for  $k^2$  (6.67  $\times$  10<sup>-8</sup>) we get

for one-sided pressure 
$$A = 6.6 \times 10^{-5} \ Td$$
 milligal (19) for all-sided pressure  $A = 13.2 \times 10^{-5} \ Td$  milligal (20)

for all-sided pressure 
$$A = 13.2 \times 10^{-5} \, Td$$
 milligal (20)

in which d is expressed in kg/cm<sup>2</sup> and T in km.

When we assume T to be 30 km and d  $10.000 \text{ kg/cm}^2$  we find for all-sided pressure an anomaly of 40 milligal and for one-sided pressure half of this value. So we see that these anomalies are by no means negligible, although they will probably never attain great figures because it seems as if 10.000 kg/cm2 is already a high figure and greater values appear improbable. This is, however, an uncertain question, because we don 't know how much pressure the crust in its deeper layers, where pressure is all-sided, can stand; it may be reasonably supposed that this is more than the values found in laboratories.

We shall now try to determine the vertical movement of the crust to which the pressure in the crust may give rise. We begin again by assuming one-sided pressure.

From the above deductions it might appear as if the reestablishment of equilibrium, that has to occur after the original isostatic equilibrium of the crust had been disturbed by the pressure d, ought to bring about a rise of the crust in order to realize the excess of mass of Td/R pro surface-unit, that is needed for equilibrium. The problem is, however, more complicated, because the pressure brings about an elastical compression of the crust, which likewise changes the amount of mass in the crust.

If E is Young's modulus of elasticity for the crust and m Poisson s constant and if the mean density of the crust is  $\varrho_c$ , we find that in every vertical column of the crust of unit crosssection, the compression causes an increase of mass of

$$\frac{d}{E} T \varrho_c - \frac{d}{mE} T \varrho_c = \frac{(m-1) T d \varrho_c}{mE}$$
 (21 A)

and, at the same time, the compression increases the length of the column by the amount

$$\frac{Td}{mE} \tag{21 B}$$

We found that the increase of mass, which is needed for maintaining equilibrium is

$$\frac{Td}{R}$$
 (21 C)

By computing these amounts, we find that the increase given by the compression is more and the excess is given by the difference

$$Td\left[\frac{(m-1)\varrho_c}{mE} - \frac{1}{R}\right] \tag{21 D}$$

If equilibrium is reestablished after the compression, this excess must disappear by a sinking of the crust of which we find the amount by dividing 21D by the density  $\varrho_s$  of the subcrustal material and so the sinking of the lower boundary of the crust is given by

$$\frac{Td}{E\varrho_s} \left[ \frac{(m-1)}{m} \varrho_s - \frac{E}{R} \right] \tag{22}$$

As the length of the column is increased by the compression, the upper boundary of the crust sinks less and so we find for the sinking of the surface of the Earth, the difference of 22 and 21 B:

$$\frac{Td}{E\,\varrho_s}\left[\frac{(m-1)}{m}\,\varrho_c - \frac{E}{R} - \frac{\varrho_s}{m}\right] \tag{23}$$

When the crust is below sea-level before and after the compression, the formulas have to be corrected. The increase of mass in the crust given by 21 A has to be diminished by the mass of sea-water corresponding to the rising of the sea-bottom as it is given by 21 B, i.e. by

$$1.03 \ \frac{Td}{mE}$$

and so the total excess of mass of formula 21 D has to be diminished by the same amount. The sinking which has to occur for reestablishing equilibrium, is now found by dividing the excess of mass in the crust by  $(q_8 - 1.03)$ , and so the formulas 22 and 23 for the sinking of the lower and upper boundaries of the crust become

lower boundary 
$$\frac{Td}{E(\varrho_s - 1.03)} \left[ \frac{(m-1)}{m} \varrho_c - \frac{E}{R} - \frac{1.03}{m} \right]$$
sea-bottom 
$$\frac{Td}{E(\varrho_s - 1.03)} \left[ \frac{(m-1)}{m} \varrho_c - \frac{E}{R} - \frac{\varrho_s}{m} \right]$$
(24)

sea-bottom 
$$\frac{Td}{E(\varrho_s-1.03)}\left[\frac{(m-1)}{m}\varrho_c-\frac{E}{R}-\frac{\varrho_s}{m}\right]$$
 (25)

The values for the sinking of the Earth's surface as they are given by 23 for land and by 25 for sea, turn out to be rather small, because by substituting for E and for m their values, the different terms between the brackets compensate each other for the greatest part. By putting

$$\varrho_{e} = 2.75$$
 $\varrho_{s} = 3.30$ 
 $m^{1}) = 4.46$ 
 $E^{2}) = 0.84 \times 10^{12}$  dynes
 $R = 6370 \text{ km}$ 
 $T = 30 \text{ km}$ 
 $d = 10.000 \text{ kg/cm}^{2}$ 

Value found by F. D. ADAMS and COKER, Deduced from bulk-modulus as determined by L. H. ADAMS, E. D. WILLIAMSON and R. E. GIBSON for granite, i.e. from the mean of the two values for pressures of  $2 imes 10^9$  c.g.s. and  $10^{10}$  c.g.s. (sea JEFFREYS, The Earth, 2nd Edition, p. 102) =  $0.507 \times 10^{12}$  dynes.

we find for formula 23:

$$108 (2.14 - 1.32 - 0.74) = 9 \text{ meters}$$

and for formula 25:

$$157 (2.14 - 1.32 - 0.74) = 13 \text{ meters}$$

These values are insignificant and small changes in the adopted values for the different quantities would make them disappear or change sign. So we may conclude that, if these adopted values are right, the surface practically undergoes no vertical movements when horizontal stresses develop.

For the lower boundary of the crust the movement is slightly greater; we find on land (formula 22) a sinking of 88 meter and at sea (formula 24) 92 meter.

For all-sided stress, the formulas have to be doubled. We can easily see that this is true because this case can be built up by superimposing on the first one-sided field of stress in the crust a second one-sided field of stress of the same strength but at right angles to the first. So all the effects get the double value and we find the following formulas for the sinking of the boundaries of the crust:

Land, upper surface 
$$\frac{2 Td}{E \varrho_s} \left[ \frac{(m-1)}{m} \varrho_s - \frac{E}{R} - \frac{\varrho_s}{m} \right]$$
 (26)

Land, lower boundary 
$$\frac{2 Td}{E \varrho_s} \left[ \frac{(m-1)}{m} \varrho_c - \frac{E}{R} \right]$$
 (27)

Sea, sea-bottom 
$$\frac{2 Td}{E (\varrho_s - 1.03)} \left[ \frac{(m-1)}{m} \varrho_c - \frac{E}{R} - \frac{\varrho_s}{m} \right]$$
 (28)

Sea, sea-bottom 
$$\frac{2 Td}{E (\varrho_s - 1.03)} \left[ \frac{(m-1)}{m} \varrho_c - \frac{E}{R} - \frac{\varrho_s}{m} \right]$$
(28)
Sea, lower boundary 
$$\frac{2 Td}{E (\varrho_s - 1.03)} \left[ \frac{(m-1)}{m} \varrho_c - \frac{E}{R} - \frac{1.03}{m} \right]$$
(29)

By substituting the same values for the different quantities, we get to the same conclusion as for the previous case: the crustal surface practically undergoes no vertical movements when horizontal stresses develop. For the lower boundary of the crust we find a slight sinking of twice the amount as for the one-sided stress; for the above example of strong stress it is less than 200 meters, on land as well as at sea.

Incase the crustal stresses would develop so quickly, that this sinking of the lower boundary of the crust could not keep up with it because of the viscous resistance of the subcrustal material, we may expect a temporary rising of the surface of the crust of maximally this amount, which will disappear when the equilibrium reestablishes itself.

This temporary rising would represent an excess of mass in the crust, which is  $\varrho_s$  times the amount of the rising on land and  $(\varrho_s - 1.03)$  times this amount at sea. So the positive anomaly will temporarily be stronger than what is given by the formulas 17 and 18; the excess of anomaly will be  $2\pi k^2$  times the excess of mass. So the maximal amount of the excess on land is given by  $2\pi\,k^2\,\varrho_s$  times the formulas 22 for one-sided stress and 27 for all-sided stress, and at sea by  $2\pi k^2$  ( $\varrho_s = 1.03$ ) times the formulas 24 and 29. This does not amount to much. For our example of a great one-sided stress of 10.000 kg/cm<sup>2</sup>, this maximum value of the anomaly is only 12 milligal for land-areas and 9 milligal for sea-areas; for all-sided stress it would be twice as great.

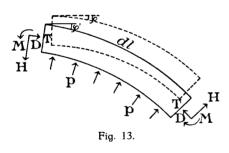
The conclusion of this paragraph, that horizontal stresses in the crust cannot bring about great vertical movements of the crust, differs from the tentative results published by the author in a previous paper  $^1$ ). This disagreement is partly caused by the taking into account of the elastical deformation of the crust at right angles to the stress-direction but chiefly by the substitution of more recently determined values for Young's elasticity modulus E.

Up to now we have only assumed elastical compression of the crust. If, however, the compression would bring about changes of the original state of the crustal materials into denser modifications, the phenomenon might assume a different aspect. Greater density increases will then occur and greater positive anomalies might temporarily come into existence but on the long run the crust would have to tend to the same equilibrium as that which has been investigated in the beginning of this paragraph. So, also in this case, the anomaly will sink back to the values given by the formulas 17 or 18. The crust will, however, in this case undergo a greater sinking.

It may be pointed out that the fact that the different terms of the formulas for the sinking of the crust incase of purely elastical deformation of the crust, neutralize each other. might be quite different for other planets. So on these planets the history of the crust might take a different course. We will not go deeper here into this speculative subject.

### B. Wave-formation by Lateral Compression of the Earth's crust.

Lateral compression of the Earth's crust may also give rise to a more complicated elastical deformation of the crust, a formation of waves. For the investigation of this phenomenon, we again assume that the crust is a rigid plate floating on a denser plastical substratum and we suppose that the deformation is so slow that the viscous resistance of the substratum may be neglected. We shall further assume that the compression takes place in one



direction only and, neglecting the curvature of the Earth at right angles to this direction, we shall treat the problem as a two-dimensional one.

Let us consider the conditions of equilibrium of an element dl of the crust. Let D be the resultant of the compression in a vertical cross-section, H the resultant shearing-force and M the resultant moment of force in this cross-section; let T be the thickness of the crust and R the Earth's radius, let  $p = \varrho y$  be the pressure pro surface-unit exerted by the substratum, which has to be

assumed proportional to the downward vertical coordinate y; let  $\varphi$  be the angle between an arbitrary fixed direction and the element dl before the deformation and  $\varphi'$  the same angle after the deformation. So we have for the angle  $\varphi$  before the deformation

$$\frac{d\varphi}{dl} = \frac{1}{R} \tag{30 A}$$

and our vertical coordinate y is tied up to the deformation by the relation

$$\frac{dy}{dl} = \sin \left( \varphi' - \varphi \right) \tag{30 B}$$

<sup>&</sup>quot;) "Maritime Gravity Survey in the Netherlands East Indies; tentative interpretation of the provisional results", Kon. Akad. v. Wet. Amsterdam, XXXIII, 1930.

The equilibrium conditions give, divided by dl,

Perpendicular to the crust 
$$\frac{dH}{dl} + D \frac{d\varphi'}{dl} + \varrho y = 0$$
 (30 C)

Parallel to the crust 
$$\frac{dD}{dl} - H \frac{d\varphi'}{dl} = 0$$
 (30 D)

Moments of force 
$$\frac{dM}{dl} - H = 0$$
 (30 E)

Lastly we get an equation by bringing the deformation, defined by the difference  $(\varphi'-\varphi)$ , in connection with the forces which are acting. As is usual for problems about elastical deformation of beams, we shall neglect the effect of the shearing-force H and attribute the whole deformation to the moment of force M. It can be easily ascertained that this is admissible and that H gives only a slight modification of the curve.

If E is Young's modulus of elasticity, we have

$$\frac{d (\varphi' - \varphi)}{dl} = \frac{M}{f} \tag{30 F}$$

in which

$$f = E I = \frac{1}{12} E T^3$$
 (30 G)

This set of equations is sufficient for determining our problem. We get the following solution. Introducing for  $(\varphi' - \varphi)$  the new variable  $\theta$ , we get by means of 30 A

$$\frac{d\varphi'}{dl} = \frac{d\theta}{dl} + \frac{1}{R}$$

and introducing the value for M given by 30 F in 30 E we obtain

$$H = f \frac{d^2\theta}{dl^2}$$

Putting these values in 30 D we get an equation, which can be integrated and we find

$$D = \frac{f}{2} \left( \frac{d\theta}{dl} \right)^2 + \frac{f}{R} \frac{d\theta}{dl} + D_0$$
 (31)

in which  $D_0$  is an integration constant, representing the value of D for a cross-section in which  $\frac{d\theta}{dl}$ , that is to say M , is zero.

Introducing the values for H , D , and  $\frac{d \varphi'}{d l}$  in 30  ${\sf C}$  we get

$$\frac{d^{3}\theta}{dl^{3}} + \frac{1}{2} \left(\frac{d\theta}{dl}\right)^{3} + \frac{3}{2R} \left(\frac{d\theta}{dl}\right)^{2} + \left(\frac{D_{0}}{f} + \frac{1}{R^{2}}\right) \frac{d\theta}{dl} + \frac{D_{0}}{fR} + \frac{\varrho}{f} y = 0$$
 (32 A)

and differentiating with regard to l in order to be able to express the last term in  $\theta$  by means of 30 B, we obtain the following equation between  $\theta$  and l:

$$\frac{d^4\theta}{dl^4} + \frac{3}{2} \left(\frac{d\theta}{dl}\right)^2 \frac{d^2\theta}{dl^2} + \frac{3}{R} \frac{d\theta}{dl} \frac{d^2\theta}{dl^2} + \left(\frac{D_0}{f} + \frac{1}{R^2}\right) \frac{d^2\theta}{dl^2} + \frac{\varrho}{f} \sin\theta = 0 \qquad (32 \text{ B})$$

As this equation gives us  $\theta$ , i.e. the angle in the same vertical between the deformed crust and the undeformed crust as a function of the coordinate l, it may be considered as the solution for the deformation. For getting this solution, however, in a practical shape, the equation has to be integrated. This presents difficulties and the writer has not succeeded in overcoming them, save for two special cases. In the first case the deformations are so small, that their second and higher powers may be neglected with regard to the first power. In the second case the curvature of the Earth may be neglected. We shall consecutively consider both cases.

### The deformations are so small that second and higher powers may be neglected.

In this case equations 32 simplify to the following shape:

$$\frac{d^3\theta}{dl^3} + \frac{D_0}{f} \frac{d\theta}{dl} + \frac{D_0}{fR} + \frac{\varrho}{f} y = 0$$
 (33 A)

$$\frac{d^4\theta}{dl^4} + \frac{D_0}{f} \frac{d^2\theta}{dl^2} + \frac{\varrho}{f} \theta = 0 \tag{33 B}$$

 $\frac{d^4\theta}{dl^4} + \frac{D_0}{f} \frac{d^2\theta}{dl^2} + \frac{\varrho}{f} \theta = 0$ (33 B)
In these equations the terms  $\frac{1}{R^2} \frac{d\theta}{dl}$  resp.  $\frac{1}{R^2} \frac{d^2\theta}{dl^2}$  have been omitted, which is obviously admissible because of their smallness with regard to the other terms of the equation. The main effect of the Earth's curvature is given by the third term of 33 A, from which it can easily be deduced; it is simply the decrease of  $\psi$  by the amount  $D_0/R_0$ , that is to say it means a rise of the crust by this amount without affecting the further deformation of the crust.

This result is in harmony with our result of page 41, where we found that we have to expect  $D_0/R$  more mass pro surface-unit in the crust than incase of isostatic equilibrium without compression. As the present deductions neglect the density changes of the crust by the compression, it is clear that we have now to find a rise of the crust of the above amount for bringing about this excess of mass. As we have, moreover, found in the first half of this paragraph that this rise will not really take place, because it is compensated by the effects of density changes and lateral deformation of the crust, we may conclude, that here also, as far as crustal movements go, the Earth's curvature has no effect.

The solution of the equation 33 B can easily be found and then we can deduce y from 33 A. We can write the solution in a simple shape by introducing the quantities

$$c = \sqrt[4]{\frac{f}{\varrho}} = \sqrt[4]{\frac{ET^3}{12\varrho}}$$

$$d = \frac{D_c}{2\sqrt{f\varrho}} = \frac{3D_c}{\sqrt{3ET^3\varrho}}$$
(34 A)

$$d = \frac{D_c}{2\sqrt{f\varrho}} = \frac{3D_c}{\sqrt{3ET^3\varrho}}$$
 (34 B)

The quantity c depends only on the elastical and other properties of the crust; it has the dimension of a length. The quantity d is proportional to the compression  $D_c$  and also depends on the properties of the crust; it has the dimension of a numerical coefficient. We have introduced here the quantity  $D_c$ , which represents the value of D for that cross-section of the crust where the shearing-force H is zero. This quantity represents, in other words, the resultant force in this cross-section, i.e. the total compressional force that works in the crust. In our case of small deformations, we may identify  $D_c$  with  $D_0$  (see formula 31).

By the introduction of c and d the solution of 33 B and A is obtained in the following shapes:

A. For 
$$d < 1$$
  $y = A_1 e^{\sqrt{\frac{1-d}{2}} \frac{l}{c}} \cos \sqrt{\frac{1+d}{2}} \frac{(l+l_1)}{c} + A_2 e^{-\sqrt{\frac{1-d}{2}} \frac{l}{c}} \cos \sqrt{\frac{1+d}{2}} \frac{(l+l_2)}{c} (35 \text{ A})$ 

B. For 
$$d = 1$$
  $y = A_0 \cos \frac{(l + l_0)}{c}$  (35 B)

C. For 
$$d > 1$$
  $y = A_1 \cos\left(\sqrt{\frac{d+1}{2}} + \sqrt{\frac{d-1}{2}}\right) \frac{(l+l_1)}{c} + A_2 \cos\left(\sqrt{\frac{d+1}{2}} - \sqrt{\frac{d-1}{2}}\right) \frac{(l+l_2)}{c} (35 \text{ C})$ 

in which  $A_0$  ,  $A_1$  ,  $A_2$  ,  $l_0$  ,  $l_1$  and  $l_2$  are integration constants.

The first case, d < 1, can only come into existence when other outward forces work on the crust besides the compression and reaction of the substratum, because all the terms of y contain factors with positive or negative powers of e which make them increase indefinitely in one or the other sense with l, and this would be impossible without other forces. Incase there are no other forces, we may conclude that no deformation will occur as long as the limit given by d = 1, i.e. by

$$D_c = 2\sqrt{f\varrho} = 1/3\sqrt{3ET^3\varrho}$$
 (36)

is not reached. We may call this the buckling limit of the crust.

When the buckling limit is just reached, we get the deformation given by 35 B. This is



a simple wave of a length  $\pi$  c, which is symmetrical with regard to the original undeformed position of the crust, i.e. the outward wave has the same height as the inward one. The height of the wave, given

by the amplitude  $A_0$ , is evidently not determined by the properties of the crust or by the amount of compression.

This wave can only come into existence when the length of the crustal beam is infinite or — incase y=0 for the ends of the beam — if it is a multiple of the wave-length  $\pi$  c. If this is not the case, a greater compression will be needed before deformation can arise. In that case we have to apply the formula of the third case, which represents two combined waves of which the lengths are

$$L_{1} = \frac{\pi c}{V^{\frac{d+1}{2}} + V^{\frac{d-1}{2}}} \text{ and } L_{2} = \frac{\pi c}{V^{\frac{d+1}{2}} - V^{\frac{d-1}{2}}}$$
(37)

The ratio of the amplitudes  $A_1$  and  $A_2$  of the two waves is determined by the conditions at the ends of the beam; about the absolute values of the amplitudes the same can be said as for the amplitude in the former case.

An important question arises with regard to the buckling limit as it is given by formula 36. If this formula should give a stress in the crust, higher than what it can stand, the buckling would never come to pass because the crust would give way before the limit was reached. The stress corresponding to the limit is, according to 36

$$\sigma_0 = \frac{1}{3} \sqrt{3 E T \varrho} \tag{38}$$

Introducing the values of page 42:

 $E = 0.84 \times 10^{12}$  dynes, T = 30 km,  $\varrho = 3.30$   $L = \pi c = 150$  km  $\sigma_0 = 5.25 \times 10^4$  kg/cm<sup>2</sup>

we find a wave-length and a stress

which is obviously more than the crust can stand.

So we may conclude that normally the crust can never buckle but that it will give way in another way before the buckling limit is reached. Smoluchowski 1) who has made an important study of this subject along the same lines as have been followed here, has already pointed out this same result, but he also pointed out that under special circumstances buckling will be possible. This case occurs when the crust is layered and when the friction between the layers does not come up to the same value as the shearing resistance in a homogeneous crust.

Let us assume that the crust consists of n layers of the same thickness and that the friction between the layers can be neglected. We can now apply our formula to one of these layers and we assume that the pressure  $p=\varrho y$  pro surface-unit of the crust is borne by all the layers for equal parts, so that each layer is subject to  $\varrho y/n$ ; this is obviously true because all the layers are supposed to undergo the same deformation. So we have to introduce in formula 38 values for  $\varrho$  and for T which are n times smaller than the values for the whole crust and we shall find a value for the stress  $\sigma_0$ , which is likewise n times smaller than what we have obtained above for the homogeneous crust.

So, if we adopt  $10.000 \text{ kg/cm}^2$  as the stress-limit which the crust can stand without breaking, we have to assume n=6 for bringing back the stress to a value below this limit, that is to say we have to assume a crust of six layers of a thickness of 5 km each. According to formula 34 A, c and the wave-length L go down proportionally to  $\sqrt{n}$ , and so for n=6 we get L=62 km.

As the values that we have introduced for the different quantities are rather uncertain, these results are likewise so, but they may give an idea about the order of thickness of the crustal layers, that could undergo a buckling. It seems likely that areas of heavy sedimentation will be the most favourable for the realization of this condition of layering of the Earth's crust.

Another circumstance may also bring about buckling in cases where the conditions are such that normally the buckling-limit could not be reached before disrupture of another kind of the crust would take place; it is easy to see that a sinking of a part of the crust would bring about buckling at a much lower compressional stress than normal, because it increases the moment of force, which acts in the crust. Now the sinking away of parts of the crust is a common phenomenon in unstable regions and so it would not be surprising if this would play a part in bringing about buckling of the crust. It is difficult to investigate this case mathematically.

Returning to the problem as it has been investigated here, we may ask another question. If the undeformed crust would originally come up to sea-level, the conditions for the deformation are complicated by the fact that the downward waves will at once be covered by water and so we have not only a pressure  $p=\varrho y$  exerted on the crust by the substratum but also a downward

<sup>1)</sup> M. SMOLUCHOWSKI, Anzeiger d. Akad. d. Wiss. Krakau. Math. Naturw. Kl. 1909. 2. S. 3.

pressure of 1.03 y pro surface-unit. So, for the downward waves, we have to introduce  $\varrho-1.03$  instead of  $\varrho$ . This brings about the necessity of treating our problem in two separate parts, one for positive y and one for negative y and to adjust the integration constants of the two parts in such a way that in the cross-section where they meet and where y=0 for both, we get the same values for  $\theta$ , H and M. This solution gives complicated formulas which are difficult to get in an explicite shape.

The next step is to determine the lowest value of the compression D' for which buckling is possible and to deduce in this case the deformation of the crust. The simplest way to find this buckling limit is to make use of the property that for this limit, the energy of deformation of the crust is equal to the work done by the pressure exerted by the substratum and the water; it is easy to recognize the truth of this statement because the only other outward forces, which work in the cross-sections at the ends, don't do any work during the deformation, the shortening of the beam being of a smaller order of magnitude than the deformations y at right angles to the beam.

In applying this rule, we find that the buckling limit D' is below the value  $D_1$  as it is given by formula 36 for the upward waves and above the value  $D_2$  as it is given by the same formula for the downward waves when introducing  $\varrho-1.03$  instead of  $\varrho$ . This buckling of the upward waves for a compression smaller than  $D_1$  can be explained by the fact that energy passes into these parts from the parts that bend downwards. We find that, approximately, D' is the harmonic mean of  $D_1$  and  $D_2$ , which can be expressed by the formula

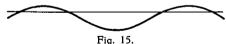
$$D' = \frac{1}{3}\sqrt{3} E \overline{T^3} \varrho' \tag{39 A}$$

in which  $\varrho'$  is given by

$$\frac{2}{\sqrt{\varrho'}} = \frac{1}{\sqrt{\varrho}} + \frac{1}{\sqrt{\varrho - 1.03}}$$
 (39 B)

For deducing the deformation of the crust in this case, we have to apply formula 35 A for the upward waves and 35 C for the downward ones. We find in this way by means of complicated deductions, that the deformation is nearly the same as if the crust was subject to the same pressure  $\varrho' y$  over its whole length, with this difference that the whole curve is shifted downwards (fig. 15). We thus find that, approximately, the upper and lower waves have the same curvature and the same moment of force.

Introducing the values for E, T and  $\varrho$  that were adopted on page 42, we find  $\varrho' = 2.70$  and a buckling stress for a homogeneous crust of



and a buckling stress for a homogeneous crust of  $4.75 \times 10^4$  kg/cm<sup>2</sup> with a wave-length L of 160 km. The stress is not much less than the value found on the previous page, where the effects of the water was

neglected, but, nevertheless, the number of layers, needed for making buckling of the crust possible, is slightly reduced.

The question may be asked whether we have not also to take into account that sedimentation will take place in the downward waves. This would again reduce the value for  $\varrho$  that we have to introduce for the downward waves, and it would do so considerably, because we should have to introduce for  $\varrho$  the small difference of density between the substratum and the sediments. With the above way of computation, we should thus find a much smaller value for the buckling stress-limit  $\sigma_0$ . It seems difficult to decide whether it is admissible to introduce

in this way into our problem this slow process of sedimentation, but there seems to be no reason to doubt that sedimentation will strongly increase the tendency towards buckling. We shall presently come back to this point. We shall now shortly consider the solutions of the equations for greater deformations.

### II. The deformations are such that their second and higher powers are not negligible.

The equation for the deformation has been found to be (32 B):

$$\frac{d^4 \theta}{d l^4} \; + \; \frac{3}{2} \left( \frac{d \theta}{d l} \right)^2 \, \frac{d^2 \theta}{d l^2} \; + \; \frac{3}{R} \, \frac{d \theta}{d l} \, \frac{d^2 \theta}{d l^2} \; + \; \left( \frac{D_0}{f} + \frac{1}{R^2} \right) \frac{d^2 \theta}{d l^2} \; + \; \frac{\varrho}{f} \sin \theta = 0$$

For the general case the writer only succeeded in finding a solution by neglecting the terms brought about by the curvature of the Earth. This is certainly admissible for the term with  $R^2$  in the denominator, but it is questionable for the third term where R appears in the first power in the denominator. This term is negligible when the deformations are small and so it did not occur in the equation 33 B. For the general case, the neglecting of the curvature is more doubtful. We shall nevertheless have to do it for obtaining a solution.

Our equation thus simplifies to

$$\frac{d^4\theta}{dl^4} + \frac{3}{2} \left(\frac{d\theta}{dl}\right)^2 \frac{d^2\theta}{dl^2} + \frac{D_0}{f} \frac{d^2\theta}{dl^2} + \frac{\varrho}{f} \sin\theta = 0 \tag{40}$$

We shall again introduce the quantities c and d given by the formulas 34 A and 34 B, but we have to pay attention to the fact that the force of compression of the crust  $D_c$  is no longer identical with  $D_0$ .  $D_c$  is the value of D for the cross-section where H=0 and  $D_0$  the value for the cross-section where M=0. The formula for  $D_c$ , based on formula 31, is given below.

The solution of 40 now takes the shape of an elliptic function. We find for the buckling-limit d=1

$$y = 2kc cn \frac{l}{c} \tag{41 A}$$

which gives

$$\sin\theta = -2k \sin\frac{l}{c} dn \frac{l}{c} \tag{41 B}$$

$$\frac{d\theta}{dl} = -\frac{2k}{c} cn \frac{l}{c} \tag{41 C}$$

$$D_{\rm c} = D_0 + 2\frac{k^2}{c^2} f \tag{41 D}$$

The quantity k is the modulus of the elliptic function. This modulus is often indicated by means of an angle a so that  $k = \sin a$ .

As the coordinate l is no longer suitable for giving a good impression of the curve, we shall introduce a new coordinate x, perpendicular to the coordinate y. We find

$$x = 2 c E \left(am \frac{l}{c}\right) - c F \left(am \frac{l}{c}\right)$$
 (41 E)

where F and E are the elliptic integrals of the first and second kind.

The curve is again symmetrical with regard to the x axis, i.e. to the line that represents the undeformed position of the crust. For getting an idea about the value of the modulus k for a certain curve, we may remark that for y=0, i.e. for  $am \frac{1}{c}=\frac{1}{2}\pi$  we find

$$\sin \frac{1}{2} \theta_0 = k \tag{42 A}$$

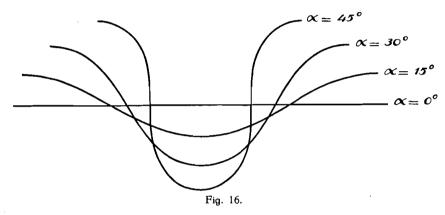
which follows at once from the general relation that can be deduced from 41 B:

$$\sin \frac{1}{2} \theta = k \, \operatorname{sn} \, \frac{l}{c}$$

Introducing the angle  $\alpha$ , we can also write 42 A in the shape:

$$\theta_0 = 2 \ \alpha \tag{42 B}$$

By means of the formulas that have been given, it is easy to deduce the shapes of the curves for different values of  $\alpha$ . The figure gives a few examples.



The solution is valid for the buckling-limit d=1. For other values of d the writer has not been able to find a general solution. For d<1, the solution is no longer applicable, because the quantities of the formulas become imaginary. For d>1, the solution remains valid when we substitute for c one of the two values

$$\frac{c}{\sqrt{\frac{d+1}{2}} + \sqrt{\frac{d-1}{2}}} \text{ or } \frac{c}{\sqrt{\frac{d+1}{2}} - \sqrt{\frac{d-1}{2}}}$$

$$\tag{43}$$

but these two special solutions don't provide the general solution in the same way as for the previous case of small deformations, by adding them together, each one multiplied by an integration-constant. The writer has not investigated under which circumstances the special solutions are stable.

When the length of the crustal beam is infinite, the crust will buckle for the limit d=1. When, however, the length is finite and when it is not a multiple of the wave-length corresponding to the buckling-limit, or when outside forces complicate the matter, another solution will have to be found for which  $d \leq 1$ . Eventually, one of the two special solutions may then satisfy the conditions. It may be pointed out that even if the length of the beam is a multiple of the wave-length for the buckling-limit incase the deformations are small, this will not continue to be so for increasing deformation, because the length of the crust for one wave increases for

increasing deformation. This follows from the above formulas, because the wave-length L is given by the equation

$$am \frac{1}{2} \frac{L}{c} = \frac{1}{2} \pi \tag{44}$$

and its solution for L depends on the modulus k, which itself depends on the amplitude of the wave.

We shall not further investigate this general case of great deformations of the Earth's crust. As far as the writer succeeded in obtaining a solution, it seems as if there is no reason to expect a difference of behaviour between the upward waves and the downward waves, even for greater deformations. It is, however, doubtful whether this conclusion would remain valid when the curvature of the Earth should be taken into account, and another point which might invalidate this conclusion is the effect of the water which will cover the downward waves. We saw in the previous part of this § that both these points have no effect on our conclusion when the deformations are small, but the question whether this is also true for greater deformations is still open.

For three reasons, however, there is cause for assuming that the downward wave will sooner reach the breaking limit than the upward one. First, the sedimentation in the downward waves gives loads on the crust, that increase the moment of force in these waves. Now it is certainly true that the erosion of the upward waves has the same effect in these waves, because the erosion causes upward forces, but it may be realized that generally there is much more submerged in these unstable areas than there is emerging and so it may be assumed that the effect of the sedimentation will be the greater one.

Secondly, the lower wave of the crust reaches down in warmer layers of the Earth and so we may expect that the higher temperature will bring about a lowering of the strength, above which plastic flow begins to occur. The downward wave will, therefore, sooner be liable to plastic deformations than the upward one.

Thirdly, the conditions with regard to the potential energy of the gravity field are more favourable for a disrupture of the lower wave. Supposing that such a disrupture will try to take the shape of a bulging of the crust on the outside of the wave, we may notice that for the upward wave such a bulge would have to be pushed up against gravity and that the density of the bulge is about 2.7. For the downward wave, the pushing down of the bulge would also require energy with regard to gravity, because the density of the bulge is lower than that of the substratum which it has to displace, but here the difference of densities, to which the energy to be spent is proportional, is only about 0.5. So there is a considerable difference in the amount of energy for both cases. Roughly speaking, their ratio is 2.7:0.5, i.e. about five times as much for the upward wave.

Resuming, we see that there is reason to suppose that the crust will sooner give way by buckling inwards than by doing so outwards. We need not point out that this conclusion is only valid when the whole phenomenon takes place so slowly, that the viscous resistance exerted by the substratum may be neglected.

#### III. The effect on gravity of a wave-formation of the crust.

The resulting gravity anomalies brought about by a wave-formation of the crust as has been discussed, can easily be derived. Although the whole crust is assumed to be in floating

equilibrium, the waves are not separately in isostatic balance, because they are kept in existence by the forces working in the crust. So the topography occasioned by the wave-formation is uncompensated. As this topography is smooth-featured, we may neglect the so-called "Gelände-Reduktion" and we may put the gravity anomaly proportional to the vertical coordinate y according to the formula of Bouguer. By substituting for y the value given by the formula 35B, we find

$$A = 2 \pi k^2 \varrho y = 2 \pi k^2 \varrho A_0 \cos \frac{(l+l_0)}{c}$$
 (45)

So we get strips of positive and negative anomalies, corresponding to the upward and downward waves of the crust. The distance from the axis of the positive strip to the axis of the negative strip is equal to the wave-length L. For the values of E, T and  $\varrho$  of page 48 we found a value of L of 150 km. The intensity of the anomalies in the strips only depends on the intensity of the wave-formation; it is independent of the properties of the crust and quite or nearly independent of the amount of compression.

The distribution of anomalies of formula 45 will always be accompanied by the field of positive anomalies as it is given by formula 17, because all the considerations of the first part of this § about the equilibrium conditions of the crust as a whole when it is under compressional stress, remain valid in our case of wave formation. These last anomalies are proportional to the compression. So, in total, the strips of positive anomalies will show greater values than what is given by 45 and the negative strips smaller ones.

# § 9. Discussion of eventual stresses exerted on the Crust by the Substratum; Convection-currents.

In discussing the crust and the substratum, we shall assume, for simplicity's sake, that there is a sharp boundary between them. For most of the conclusions this assumption is not material; they remain likewise valid incase there should be a more or less gradual transition of the properties.

There is no doubt that the substratum is plastic but that it has a high viscosity. So it is not out of the question that the substratum should exert other forces on the crust than pure hydrostatic pressure, and this could give rise to deviations from isostatic equilibrium. These viscous forces must be connected with dynamic processes and here we may distinguish between two conceivable possibilities, temporary processes and processes that are more or less stationary over long geological periods. In the last case the resulting dynamic forces, which cause the deviations from isostasy, will likewise have a stable character.

As temporary dynamic processes, we may mention in the first place all readjustments of equilibrium that occur after the balance has been disturbed by other phenomena. There are many of these balance disturbing phenomena taking place in the crust and it may be considered possible that they also occur in the substratum. We may, for instance, admit the possibility of changes of state or magmatic differentiations going on in the substratum under the effect of changes of temperature and pressure; the cooling of the Earth might perhaps lead to such processes. If these changes of state are irregularly distributed over the Earth, we get a disrupture of the equilibrium, which will give rise to currents in the substratum and the high viscosity must cause a considerable time-lag in the readjustment of the equilibrium. Because of this time-lag we get temporarily a disturbance of the equilibrium which will show in the gravity at the Earth's surface as a deviation from isostasy.

In the crust there are many phenomena taking place that cause a disturbance of the equilibrium. We may again admit the possibility of changes of state going on under the effect of changes of temperature and pressure, but besides these hypothetical phenomena, there are many others at the surface that are well-known. There are erosion and sedimentation, which in many cases represent great mass-transportations. The same may be said of volcanic eruptions and intrusions, which may be local but of which also instances are known occurring over wide areas. Another instance is found in the ice-loads on the crust in the polar regions, that varied considerably in consecutive periods as well as regards the extent of the covered area as the thickness of the load. Lastly there are eustatic changes of sea-level which constitute wide-spread although small disturbances of the equilibrium. In all these cases, the time-lag in the readjustment of the equilibrium must cause deviations from isostasy in the gravity at the Earth's surface. The question is how great are the deviations that we may expect in this way.

Now, the indications that we possess, point in the direction that this is not much; the time-lag appears not to be great enough for causing large deviations. These indications are provided by gravity values in river-deltas and in areas that have been covered by ice in the glacial periods and which, since then, have been freed from the load. In both cases active or recent processes are in question. The values given by the Mississippi delta and by the Nile delta don't show indications of the positive values that ought to be present when the sinking of the crust under the load of the deposited material would show an appreciable lag. If there is any effect, it is covered over by other deviations in those areas.

The gravity values found in the Baltic area do show a slight effect, which rarely exceeds — 40 milligal, and the rising of the land, that is stated to be of the order of 1 cm pro year in the land round the northern half of the Baltic, also shows that here indeed, the readjustment of the equilibrium seems still to be going on. A gravimetric survey of the Baltic itself will be important in this regard because this would complete the facts. Up to now no figure for the time-lag has been derived from the figures that are known; from the above data it would appear to follow that the adjustment takes away about 1/40.000 part of the disturbance per year, but this figure cannot be considered as giving more than the order of magnitude of the rate of readjustment. For getting a better insight in this figure, we should have to make a deeper study of the whole process by applying the equations for the movement of fluids with great viscosity. We shall afterwards come back to these processes.

We may conclude, from the absence of any effect in the deltas and the smallness of the effect in the Baltic area, that for explaining strong anomalies, we should have to assume great phenomena that are still active or that have been active only a short time ago.

As to stationary dynamic processes, the principal possibility that suggests itself, is that of convection-currents. We shall consider this possibility more in detail.

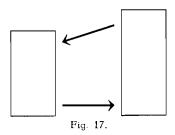
#### Convection-currents in the Substratum.

It is well-known that convection-currents in the substratum have already been supposed by several geologists and geophysicists. One of the advocates of this hypothesis nowadays, Arthur Holmes, mentions the names of Hopkins (1839) and O. Fisher. In later years it has been brought forward by R. Schwinner and by Holmes.

Leaving aside whether convection would be likely when the distribution of the temperature in the Earth were perfectly regular in horizontal sense, i.e. when the temperature were

everywhere the same in horizontal layers, the writer thinks that in the actual Earth, of which the continental crust is assumed to be considerably richer in radio-active constituents than the oceanic crust, and where, therefore, differences of temperature must occur below the crust, there can be no doubt that convection-currents must develop.

Let us first consider the mechanism of this phenomenon and afterwards investigate its consequences for the gravity field. In comparing a column of the substratum below the continents



to one of the same weight below the oceans, the first must have a higher temperature than the second and so it will have less density and greater height. Supposing that in the beginning both columns were in hydrostatic equilibrium at their base, this would not represent equilibrium for their higher parts, as is shown immediately by the fact that the surface of the first is higher than that of the second. The result would be a flowing of material in the upper part from the higher towards the lower column. There can be no doubt that such a flow is possible in the substratum, because it is

proved to occur when the isostatic balance of the crust is readjusted after other disturbances of equilibrium.

The increase of weight of the second column must bring about an increase of pressure at its base and this must give a contrary current in the lower part from the lower to the higher column. This process will attain a dynamic equilibrium when the transportation of mass from one column to the other by the upper current is exactly compensated by the backward transportation by the lower current; a stationary convection-current has then be set going.

The height of the columns is determined by the obvious requirement, that the convection-layer must have homogeneous density under the same conditions of temperature and pressure. The convection will therefore maximally reach down to the first discontinuity surface in the substratum below the crust. According to the indications given by seismology, we shall presently assume a depth of this surface of 1200 km. If no homogeneous layer would exist below the crust, i.e. if the density would gradually increase downwards, no convection would be possible, but the writer does not think that this is likely, because all the indications of Geochemistry and Seismology point to a separation of the materials in the Earth in more or less homogeneous layers.

The fundamental assumption on which the mechanism of the convection, as it is represented here, is based, is the difference of temperature at the lower boundary of the crust. There does not seem to be reason to doubt this assumption. A first cause is found in the effect of the seawater which cools the crust to a temperature of 4° at a depth of several km, while the continental crust at the same depth is considerably warmer. A second cause has already been mentioned, the difference of radio-activity of the continental and the oceanic parts of the crust. Jeffreys mentions the following figures for the mean radio-activity of different materials: For the heat generation in  $10^{-12}$  calorie per second per cubic centimeter he gives for granite 1.3, for basalt 0.50, and for plateau basalt 0.36. 1) Now there can be no doubt about the fact that the layer of granite is considerably thicker in the continents than in the oceans, where it may even be entirely absent, and where in that case the surface layer would probably be basaltic. So the generation of heat in the surface layer of the crust is doubtless larger in the continents than under the oceans. It is difficult to say what the radio-activity is in the deeper layers as

The Earth", 2nd edition, p. 143.

there is a difference of opinion about their constitution, but it appears unlikely that there would be a reversion of the above relation in such a way that the difference would be compensated.

We must suppose that the convection-layer is supported by a layer, that has at least the same plasticity. Under these circumstances, the convection-layer will adjust itself in floating equilibrium on this lower layer and so the unloading of the rising column and the excess of weight of the descending column must bring about vertical movements of these colums with regard to the lower layer till equilibrium is readjusted again. A simple consideration shows, that this readjustment of balance does not take away the differences of pressure between the two columns in their lower parts, although it reduces them, and so the mechanism of the convection remains as it has been described.

We may now examine the effect of the whole phenomenon on gravity. Superficially looking, it might appear as if, on the average, we ought to find about normal gravity, because we have supposed that the whole convection-layer will settle itself in floating equilibrium on the lower layer, and it might be expected that this would imply the equality of mass in all vertical columns of the same cross-section if we should extend them till well down in the lower layer. This, however, is not true because of the dynamic character of the phenomenon and so we have to make a closer investigation before we can determine the effect on gravity.

This investigation has to be based on the equations of motion for viscous fluids. In their most general shape, they are given by the following sets of equations. The first gives the relation of the stresses to the movement

$$p = \frac{1}{3} (\sigma_{x} + \sigma_{y} + \sigma_{z})$$

$$\sigma_{x} = -p - \frac{2}{3} K \nabla v + 2K \frac{\delta v_{x}}{\delta x} \qquad \tau_{x} = K \left( \frac{\delta v_{y}}{\delta z} + \frac{\delta v_{z}}{\delta y} \right)$$

$$\sigma_{y} = -p - \frac{2}{3} K \nabla v + 2K \frac{\delta v_{y}}{\delta y} \qquad \tau_{y} = K \left( \frac{\delta v_{z}}{\delta x} + \frac{\delta v_{x}}{\delta z} \right)$$

$$\sigma_{z} = -p - \frac{2}{3} K \nabla v + 2K \frac{\delta v_{z}}{\delta z} \qquad \tau_{z} = K \left( \frac{\delta v_{z}}{\delta y} + \frac{\delta v_{y}}{\delta x} \right)$$

$$(46)$$

 $\sigma_x$ ,  $\sigma_y$  and  $\sigma_z$  are the normal components of the stresses and so their mean value p may be called the pressure of the fluid.  $\tau_x$ ,  $\tau_y$  and  $\tau_z$  are their shearing components. K is the viscosity and v is the velocity with its components  $v_x$ ,  $v_y$  and  $v_z$ .  $\forall v$  is the divergence of the velocity-vector, given by the formula

$$\nabla v = \frac{\delta v_x}{\delta x} + \frac{\delta v_y}{\delta y} + \frac{\delta v_z}{\delta z}$$

The second set of equations are the equations of motion:

$$\frac{\delta p}{\delta x} = X + K \nabla^2 v_x + \frac{1}{3} K \frac{\delta}{\delta x} \nabla v - \varrho \frac{d v_x}{d t}$$

$$\frac{\delta p}{\delta y} = Y + K \nabla^2 v_y + \frac{1}{3} K \frac{\delta}{\delta y} \nabla v - \varrho \frac{d v_y}{d t}$$

$$\frac{\delta p}{\delta z} = Z + K \nabla^2 v_z + \frac{1}{3} K \frac{\delta}{\delta z} \nabla v - \varrho \frac{d v_z}{d t}$$
(47 A)

X, Y and Z are the forces per unit of volume, working on the fluid and  $\varrho$  is its density. The operator  $\nabla^2$  is the operator of Laplace

$$\nabla^2 = \frac{\delta^2}{\delta x^2} + \frac{\delta^2}{\delta y^2} + \frac{\delta^2}{\delta z^2}$$

 $\frac{d}{dt}$  is the derivative with regard to the time for a moving particle of the fluid and so, if  $-\frac{\delta}{\delta t}$  is the derivative in a fixed point, we have

$$\frac{d}{dt} = \frac{\delta}{\delta t} + v_x \frac{\delta}{\delta x} + v_y \frac{\delta}{\delta y} + v_z \frac{\delta}{\delta z}$$
 (47 B)

Lastly we have an equation for the divergence of v, which is derived from the properties of the fluid with regard to compressibility and temperature. When E is its modulus of elasticity, m Poisson's ratio, n its linear temperature coefficient and  $t^{\circ}$  the temperature, we get

$$\nabla v = -\frac{3(m-2)}{mE} \frac{dp}{dt} + 3n \frac{dt^{0}}{dt}$$
 (48)

In two cases, these equations may be considerably simplified.

- 1. The movements, the pressure and the temperature are stationary and the velocity v and its derivatives are so small that terms containing their second power may be neglected.
- 2. The viscosity K is large and the velocity v and its derivatives are so small that even terms containing them in the first power may be neglected unless they are multiplied by the viscosity K. The pressure and the temperature are assumed to be stationary or slowly variable.

In both cases the last two terms of the equations 47 A may be neglected. For the last term this follows at once from the above assumptions. As to the last term but one, we assume that the factors of dp/dt and of  $dt^0/dt$  in formula 48 are so small, that in multiplying them with the components of the velocity according to formula 47 B, applied to p and  $t^0$ , they are negligible even after multiplication in formula 47 A with the viscosity K. The variability of p and  $t^0$ , represented by the first term of formula 47 B, is assumed to be so small that this first term does not perceptibly exceed the other terms in this formula.

So our equations of motion simplify to

$$\frac{\delta p}{\delta x} = X + K \nabla^2 v_x$$

$$\frac{\delta p}{\delta y} = Y + K \nabla^2 v_y$$

$$\frac{\delta p}{\delta z} = Z + K \nabla^2 v_z$$
(49)

We may state this in a shape, comparable to the principle of d'Alembert for dynamic problems with greater velocities:

A problem satisfying one of the above sets of conditions can be treated as a static problem by adding everywhere a force  $K \nabla^2 v$  per unit of volume.

Examining the conditions of the second case, we see that they are fulfilled in the substratum of the Earth. So we can treat all problems regarding the substratum by means of

this rule, that is to say that it is not only allowed to apply it to the stationary processes of convection-currents but also to temporary processes like readjustments of isostatic equilibrium.

We shall now make use of the rule for our convection-problem. It gives immediately the additional forces caused by the movement, and these forces must disturb the static equilibrium that would correspond to isostasy. Choosing the y coordinate vertically downwards, the second formula 49 gives the vertical component  $k \nabla^2 v_y$  of this force and so the resultant vertical force, working on a column of the convection-layer of unit horizontal cross-section, is the integral of this quantity over the thickness H of this layer. This resultant force must correspond to a defect of mass in the column of the same weight, which must bring about isostatic anomalies at the Earth's surface. For simplification, we shall assume that the field is constant in a horizontal sense over an extensive area. In that case the anomaly must be, if  $k^2$  is the Newtonian gravitation constant,

$$A = -2 \pi k^2 \frac{K}{g} \int_{0}^{H} \nabla^2 v_y \, dy \tag{50}$$

So we find that the anomalies are connected with vertical movements in the substratum and not directly with horizontal ones. For getting a nearer view on the relation of the movements to the anomalies, we may make use of a theorem of vector analysis. The field of  $\nabla^2 v_y$  represents a field of divergences of the gradient field  $\nabla v_y$ . So the integral of  $\nabla^2 v_y$  over a certain part of the convection-layer may, according to the theorem of Gauss, be found by taking the integral of the outward flux of  $\nabla v_y$  through the boundary of the area. In doing this we have also to include the upper and lower boundary of the layer.

We may apply this to a field of positive anomalies. Such a field would, according to formula 50, correspond to a negative integral of  $\nabla^2 v_y$  in the substratum. From the above reasoning we may conclude that this must mean, on the average, an inwardly directed gradient of  $v_y$ , that is to say greater values of  $v_y$  inside the field than outside. So we find that a field of positive anomalies points to a downward current in the substratum.

This result can easily be understood. Incase of a downward current, the viscous resistance working on the column has an upward resultant and this must correspond to an excess of weight of the column, causing positive anomalies.

It is a remarkable confirmation of the convection hypothesis that at sea several extensive fields of positive anomalies have been found while this is not the case on land; this points to descending currents in the oceans as we have to expect according to the lower temperature of the oceanic crust. So the distribution of the fields of anomalies over the Earth, as far as it is known now, seems to be in harmony with the hypothesis.

Another remarkable confirmation is found in the deep basins in the East and West Indies as the Banda Sea, the Celebes Sea, the Gulf of Mexico and the sea west of Cuba, which all show rather strong positive anomalies that are larger where the depth is greater. Most of the geologists think that these basins must have originated by vertical subsidence in a fairly recent geological period. The combination of these two facts is suggestive, as it clearly points to the development of a sinking current. The writer has not found another hypothesis that could give as satisfactory an explanation.

In chapter V the gravity results will be examined more in detail and we shall there come back to this subject at greater length.

For a further investigation of the convection-currents, we shall make a supposition regarding the distribution of the vertical speed  $v_y$  in the descending and ascending currents. For simplifying the matter, we shall assume that the phenomenon does not depend on the coordinate z, i.e. that it is two-dimensional. We know that  $v_y$  must be zero at the upper and lower boundary of the convection-layer, i.e. for y=0 and for y=H. Likewise it must be zero at the borders of the column, i.e. for  $x=\pm \frac{1}{2}D$ , D being the diameter of the column. So we shall put, as the most simple assumption in harmony with these boundary conditions,

$$v_y = 4 \ v_m \left( 1 - \frac{4 \ x^2}{D^2} \right) \left( 1 - \frac{y}{H} \right) \frac{y}{H} \tag{51}$$

in which  $v_m$  is the maximum value of the downward speed in the centre of the column. The actual distribution will, no doubt, be more complicated, but as the deduction is only meant for a first approximation, the above assumptions may do for our purpose. It follows that

$$abla^2 v_y = -\frac{32 v_m}{D^2 H^2} (\frac{1}{4} D^2 + H y - x^2 - y^2)$$

and, according to formula 50, we obtain

$$A = \frac{32}{3} \pi k^2 \frac{K (D^2 + H^2)}{g D^2 H} v_m \tag{52}$$

The sign of these formulas agrees with what we deduced already; positive anomalies correspond to positive values of  $v_y$  that is to say to downward currents.

This formula would give the means to compute the speed of the current, if we knew the mean viscosity K and the thickness H of the convection-layer. For H we may perhaps substitute the value of 1200 Km as it is given by seismology, but for K no reliable figure is available. According to Jeffreys, the 14 monthly variation of latitude leads to assume that the mean viscosity must exceed  $5 \times 10^{20}$  dyne sec/cm², 1) but further no data are known. A figure that may lead to an estimate, is the rate of rise of the Scandinavian area when we adopt it as being caused by the readjustment of isostatic equilibrium. Putting this rise at 1 cm per year in the central part of the area and the mean anomaly of this part at — 40 milligal, we can make the following rough approximation. We know the vertical upward speed  $v_m$  in the middle of the rising area at the surface of the substratum to be 1 cm per year or  $3.2 \times 10^{-8}$  cm/sec and we suppose that  $v_m$  decreases linearly with the depth. The diameter of the area, which we assume to be circular, being D, we put

$$v_y = v_m \left( 1 - \frac{4(x^2 + z^2)}{D^2} \right) \left( 1 - \frac{y}{H} \right)$$
 (53)

According to formula 50, this leads to an anomaly

$$A = 16 \pi k^2 \frac{KH}{gD^2} v_m \tag{54}$$

Introducing the values for  $v_m$  of  $3.2 \times 10^{-8}$  cm/sec and for A of 40 milligal, and supposing the compensating current to reach down to a depth of 1200 km, we find, if we put the diameter of the area D at 1000 km,

$$K = 4 \times 10^{22}$$
 dyne sec/cm<sup>2</sup>.

<sup>1)</sup> H. Jeffreys, "The Viscosity of the Earth", M.N.R.A.S. Geophys. Suppl. 1, 1926, p. 424.

When we apply this value for K in formula 52 and when we put the diameter of the convection-current D at 1200 km and H likewise at this value, we obtain for an anomaly-field of 40 milligal a value for the downward speed  $v_m$  in the centre of the column of one centimeter per year.

We may remark that the above deductions show that the order of magnitude of this speed must be the same as that of the rise of the ground in Scandinavia if the anomalies, the depths and the horizontal dimensions of both phenomena don 't differ too much. Another assumption for the depth H, if the same in both cases, has only a slight effect on the result.

In connection with the hypothesis of convection, a few important questions arise, which we shall shortly examine, although they have no immediate bearing on the anomalies. The first question is, whether the convection can cause tangential stresses in the Earth's crust and the second regards the temperature difference of the substratum below the continents and below the oceans. We shall express our formulas concerning these questions in the difference in height h of the surface of the substratum above the rising and above the descending currents or, more accurately expressed, in the difference in height that the free surface of the substratum would show in these parts, if it were not covered by a crust.

The difference of pressure between both ends of the upper horizontal part of the convection-current varies between  $\varrho$  g h at the upper boundary and zero at the lower boundary of this current,  $\varrho$  being the density of the substratum. According to these values we shall make the roughly approximate assumption that the difference of the total horizontal resultant of the pressure on both ends of the current is  $\frac{1}{2}\varrho$  g h s, in which s represents the vertical diameter of the current. We may recall that the phenomenon is assumed to be independent of the z coordinate and the dimension in this sense is accordingly chosen equal to the unit of length.

Half of this force must be transferred on the lower boundary of the crust in the shape of a viscous drag exerted by the current This drag may thus be estimated at  $\frac{1}{4} \varrho g h s$ . Assuming that the crust, between the rising and descending currents, will bear the full amount of the drag and that the thickness of the crust is T, we find, as a consequence of this, a stress in the crust of

$$o = \frac{1}{4} \varrho g h - \frac{s}{T} \tag{55}$$

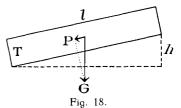
We shall substitute for  $\varrho$  a value of 3.2 and for T a thickness of 30 km but it is difficult to make an estimate of the vertical diameter of the current s. We may predict that this current must be narrower than the lower horizontal current in contrary sense, because it is easy to see that the difference of the pressure at both ends of this lower current must be less than for the upper one. As the sum of the diameters of the upper and the lower current together equals the thickness H of the convection-layer, which we have assumed to be 1200 Km, we shall put the diameter of the upper current at 400 km. This figure is, of course, highly problematical. Substituting this value, formula 55 becomes, if h is expressed in km

$$\sigma = 1000 h \text{ kg/cm}^2 \tag{55 A}$$

This is not however, the only cause of stress in the crust brought about by the convection. Another effect follows from the tendency of the crust to slide down from the higher to the lower parts of the surface of the substratum. This tendency is comparable to what DALY supposes

in his theory about the sliding continents 1) and analogous suppositions form also part of the

theories of  $H_{AARMANN}$  and others 2), but these authors look for the cause of the inequalities of the surface of the substratum in other directions. The stress in the crust brought about by this effect can be easily deduced. Considering the part of the crust of a length l between the bulge and the depression of the substratum, we see that the difference in level of the two ends h causes a compressive force in the crust



$$P = \frac{h}{I} G = \varrho g h T$$

and so the resulting stress in the crust is

$$\sigma = \varrho \ g \ h \tag{56}$$

By substituting for  $\varrho$  the value 2.75 we get

$$\sigma = 270 h \text{ kg/cm}^2 \tag{56 A}$$

This part of the stress is to be added to the first part given by formulas 55 and 55 A. We see that it is smaller, but for lower estimates of the diameters of the convection-current, the difference is less. In total we obtain

$$\sigma = 1270 h \text{ kg/cm}^2 \tag{57}$$

It is difficult to make an estimate of the difference in level h of the substratum over the rising and descending currents. For the currents that may be supposed below the deep basins in the East and West Indies mentioned on page 58, there is reason to assume that h is equal to the full depth of these basins, because it is an obvious supposition that the subsidence of these basins has originated because of the developing of the convection-current. Such a value of h of several km would imply great values for the stress in the crust of many thousands of atmospheres, and so it appears possible that the convection phenomenon can be responsible for important tectonic disturbances.

The fact that the flux of the convection-current must be the same for the cross-sections of the horizontal and vertical parts of the current, provides us with a relation between the anomalies and the differences of level h, As only a rough approximation is possible, we shall simplify formula 52 by substituting for D/H + H/D the value 2, which is admissible for a fairly wide range of the ratio D/H. As the flux F for the middle cross-section of this current, i.e. for  $y = \frac{1}{2}H$ , is equal to  $\frac{2}{3}v_mD$  (formula 51), we get

$$A = 32 \pi k^2 \frac{KF}{gD^2}$$
 (58)

For the horizontal current we obtain, by applying the first of formulas 49 and by making an analogous assumption to formula 51 for the horizontal speed  $v_x$  in this current,

$$h = 32 \frac{KF}{\varrho g s^2} \tag{59}$$

<sup>1)</sup> R. DALY, "Our Mobile Earth".

<sup>2)</sup> E. HAARMANN, "Die Oscillationstheorie".

From these formulas we deduce

$$h = \frac{A}{\pi k^2 \varrho} \left(\frac{D}{s}\right)^2 \tag{60}$$

and, introducing the values for  $k^2$  and  $\rho$ , and expressing A in milligal, we obtain

$$h = 15 \left(\frac{D}{s}\right)^2 A \text{ meters} \tag{60 A}$$

Substituting for D, s, and A the values 1200 km, 400 km and 40 milligal, which we have substituted before, we find a value of h of 5000 meters. The whole deduction cannot give more than the order of magnitude, because so many of the assumptions are uncertain, but the agreement with the order of magnitude of the depth of the basins is remarkable. This may inspire us with some confidence in the assumptions.

The last point that merits a short investigation is the difference of temperature of the substratum at the top of the rising and descending currents. In the following way we may get an idea of the order of magnitude of this difference. We assume that the difference in level h of the surface of the substratum is exclusively caused by the difference of temperature of the columns of the substratum. This assumption cannot be more than a rough approximation, because we neglect in this way that mass flows from the higher towards the lower column. Now there is no doubt that part of the effect of this flow on the difference in level is compensated by the sinking of the lower column that is brought about by the tendency towards readjustment of the equilibrium with regard to the supporting layer below, but part of it remains and we have to neglect this effect.

We shall further assume that the difference of temperature A of the two columns is zero at the bottom of the convection-layer and that it increases upwards in a steadily increasing way so that it is everywhere proportional to the square of the height above the bottom. We thus take into account that the cause of the temperature difference is situated at the top of the substratum. So we put

$$\Delta = c (H - y)^2 \tag{61}$$

This assumption probably underestimates  $\Delta$  in the middle part of the convection-layer, for it neglects an effect which hitherto has not been taken into account. When the temperature difference at the top of the substratum has once started the current, the vertical displacement itself brings about an increase of  $\Delta$  because of the vertical temperature gradient that is already present in the substratum as a consequence of the cooling of the Earth. This effect must cause an acceleration of the current and a further accentuation of the temperature difference of the two columns. It especially increases  $\Delta$  in the middle part because the vertical speed is greatest here and so it may well be that a linear increase of  $\Delta$  with the height above the bottom, or even a still greater value in the middle part, would be nearer to the truth. This would diminish the value of  $\Delta$  at the top in proportion to the mean value of  $\Delta$  over the whole layer and as this mean value determines the sinking of the surface, we may conclude that this effect will reduce the value of  $\Delta$  at the top that is required for a certain sinking. So, when we neglect it, we are likely to over-estimate the value of the temperature difference at the top of the substratum.

If n is the coefficient of linear expansion of the substratum, we obtain the difference in height for two columns of unit horizontal cross-section, that contain the same amount of mass,

by integrating 3 n  $\Delta$  dy over the height H of the columns. This gives for the assumption of formula 61

$$h = c n H^3$$

and, expressing h in the difference of temperature  $A_0$  at the top of the layer

$$h = n H \Lambda_0 \tag{62}$$

This allows to compute  $\Delta_0$ . Using the value for n that Jeffreys uses in "The Earth" (2nd Ed. p. 281), we have for a temperature of  $t^0$ 

$$n = 7 + 0.024 t^0 \times 10^{-6}$$

Substituting for  $t^0$  the value of 1000°, which seems admissible for an average of the temperature of the upper half of the convection-layer, we get a value of n of  $31 \times 10^{-6}$ . Introducing this in formula 62, we find for the assumption of H of 1200 km and of h of 5000 meters

$$\Delta_0 = 130^{\circ}$$

This difference does not appear to be inadmissible and, according to what has been said, a smaller value will probably be sufficient.

So we get to the conclusion, as far as this rough approximation allows a decision, that on this account there does not appear to be an objection against admitting the hypothesis of convection-currents in the Earth.

The considerations about temperatures, crustal stresses and speeds of the currents are problematical and the writer should not wish to attach too much importance to them. Eventual doubts, however, don't affect the main conclusions about the probability of convection-currents and the explanation that thus can be given of the extensive fields of positive anomalies which have been found at sea.

Besides the vertical movements of the crust that must result from the differences in level of the substratum caused by the convection, there is still another effect in vertical sense of this phenomenon. The extensive fields of positive and negative anomalies that it brings about, must affect the position of the geoid. In the second part of this chapter we have seen that generally fields of positive anomalies are accompanied by elevations of the geoid and fields of negative ones by depressions. So, according to what has been said, the elevated parts of the geoid ought mostly to occur in the oceans and the depressions in the continents.

We see that the shape of the geoid is intimately connected with the problem of the convection hypothesis. If this hypothesis proves to be true, we shall have to recognize that the Figure of the Earth is dominated by these phenomena and so our view-point is confirmed that the principal object of Geodesy, the determination of the Figure of the Earth, is narrowly related to the great geophysical problems.

## § 10. Summary: Interpretation of extensive fields of anomalies of the same sign.

In this  $\S$  a short summary is given of the results of the former  $\S\S$  concerning the interpretation of extensive fields of anomalies of the same sign.

We have seen that these fields of anomalies cannot be explained by deviations between the geoid and the ellipsoid. We have likewise found that only fields of small anomalies can be brought about by a wrong method of isostatic reduction: this could lever give fields of more than ten or, at the highest, twenty milligal. In most cases, moreover, fields of this kind can be easily recognized.

For the explanation of stronger fields, we have found three possibilities. First they may be caused by strong horizontal compression in the Earth's crust but the stresses that we have to assume, even incase the compression works from all sides, are considerable (formula 17 and 18).

Secondly, they may be caused by phenomena that have disturbed the isostatic equilibrium, as e.g. changes of state, magmatic differentiations, sedimentation, erosion, ice-loads, etc., but for adopting this explanation, we have to assume that the phenomena have acted very recently or that they are still going on, because otherwise the isostatic equilibrium would already have been reestablished. When extensive fields have to be explained, it will generally be difficult to admit the possibility of such wide-spread and recent phenomena.

Thirdly, they may be caused by convection currents in the substratum ( $\S$  9). The writer thinks that in many cases this explanation will be the most probable one. Incase there is reason to adopt it, the anomalies can give valuable information regarding the extension and the intensity of these currents.

The existence of these currents will in two ways affect the position in vertical sense of the Earth's surface. First, the fields of anomalies will bring along deviations of the geoid and in this way the Figure of the Earth depends on these phenomena. Secondly, the convection will cause vertical movements of the Earth's crust of much bigger extent than the deviations of the geoid and in contrary sense; these last movements will generally accentuate the elevations and depths of the topography. We shall have to expect a sinking of the crust in the oceans accompanied by positive anomalies and by an elevation of the geoid, and we ought to find the centrary effect on the continents.

### CHAPTER II.

# Expedition of Hr. Ms. O 13 in the Atlantic. July 5—August 14, 1932.

### § 1. Introductory, Object and Preparation of the Expedition.

In the summer of 1932 the Netherlands Navy has again been willing to organize a submarine expedition for the determination of gravity; for one month and a half the Minister of the Navy, his Exc. Mr. Deckers, allotted a submarine for this purpose. Sincere thanks are due to him for this renewed proof of willingness to promote science and for the important contribution that has thus been given.

The object of the expedition was to investigate especially those parts of the Atlantic, that are seismically active. In this way data would be obtained that would allow a comparizon with the gravity results in other seismic areas as the East and West Indies. It was hoped that thus an idea would be got whether the tectonic processes in the Atlantic have the same character as those of the geosynclinal areas of the Earth's crust.

The expedition of Hr. Ms. K XIII in 1926, reported in chapter IV of the first volume of this publication, had already given many stations in the Atlantic, but their mutual distance was usually about 200 miles, and as the expeditions of 1929 and 1930 in the East Indies as well as those of the American Navy of 1928 and 1932 in the West Indies had revealed the existence of narrow strips of strong negative anomalies of not more than about hundred miles in cross-section, these results did not give sufficient hold on the problem; it would have been possible that we had skipped such a strip without discovering it. So it was necessary to put the stations of the new expedition at shorter distances from each other. Normally they have been taken 50—60 miles apart and only exceptionally distances up to 75 miles have been admitted. These shorter distances of the stations have brought about that the expedition was rather strenuous because it implied submerging at least three times per twenty-four hours.

Tam's has shown a few years ago that most of the earthquake-centres in the Atlantic are concentrated over the Mid-Atlantic ridge and so the programme of the expedition was chosen in such a way that two profiles were observed at right angles to this ridge, one to the north of the Azores and one to the south-west of these islands. Besides this area, another strip was also worth while investigating, i.e. the strip connecting the strait of Gibraltar with the Azores. It is likewise more or less seismic and several geologists consider it possible that the tectonic axis of the Alpine geosyncline continues in this direction. A few even suppose that it goes on beyond the Azores towards New Foundland. In connection with these considerations,

the programme was planned to provide four profiles over this strip, one to the west of the Azores, two to the east of them and one crossing the line of the islands, over the island of São Miguel.

The stations 426—486 on the world-map show the programme as it has been carried out. In returning from Madeira to Holland, a continuous series of stations was made in a route parallel to the continental coast at a distance of a few hundred miles and so not only an eventual tectonic axis striking westwards from Gibraltar would be found out but also all other effects that continue from the continent in the Atlantic. In this way it was expected that a contribution might be obtained to the question whether the ocean-floor reacts in a similar way as the continental crust on eventual tectonic disturbances.

The observations of the expedition were to be made with the apparatus for maritime gravity survey, as it had been developed in the previous years. For a description, the writer may refer to the publication of the Netherlands Geodetic Commission, "Theory and Practice of Pendulum Observations at Sea". The old pendulums, however, had been replaced by a new set, because the observations made in 1931 in the North Sea had shown that they were no longer sufficiently stable. Probably the damage done by the accident during the expedition of 1929 in the Netherlands East Indies had been more serious and lasting than was expected at first.

The new pendulums were constructed by the "Nederlandsche Seintoestellenfabriek" at Hilversum according to the plans of the writer. He resolved to apply the minimum principle according to which a slight shift of the knife-edge in the pendulum-body has no appreciable effect on the time of oscillation. This principle is realized when the distance of the centre of gravity to the knife-edge is half of the mathematical length of the pendulum. On the other hand the writer wished to avoid the great damping, which is adherent to the cylindrical shape that is usually given to minimum pendulums. This object was attained by keeping to the old shape of the Sterneck pendulums with the exception of the neighbourhood of the knife-edge, where so much mass was added that the centre of gravity was brought upwards till it was half-way between the knife-edge and the so-called oscillation-point. The additional mass does not perceptibly increase the damping because it is near the knife-edge. The pendulums were again made of brass, which had proved satisfactory for sea gravity work because of its absence of magnetic effects. Their time of oscillation was chosen in such a way, that it differed more from the half-second than that of the old pendulums. This was done in order to get a coincidenceinterval, even when using mean time chronometers, that is not too big. For De Bilt the interval for mean time chronometers is about a hundred seconds.

The pendulums were made towards the end of 1931 and were used for the first time for the expedition of the U.S. Submarine  $S \sim 48$  of the American Navy in the spring of 1932. The observations of this expedition, made by means of the apparatus of the Netherlands Geodetic Commission, were executed by the writer assisted by Dr. Harry H. Hess and Mr. Townsend T. Brown.

The expedition of the O 13 thus was already the second one for which the new pendulums were used. They have behaved fairly satisfactorily although they have not been absolutely stable. We shall come back to this point in the third part of this chapter where we shall treat of the computation of the results.

No special measures were necessary with regard to wireless time-signals, because it might be expected that the rythmic signals of the European stations would be easily audible over the whole area.

For the soundings during the expedition the echo-method was adopted according to the same way of working as during the previous expeditions. The signals were to be sent out by the ordinary Fessenden Sonic Apparatus which is on board the submarines for mutual communication during submerging. The time was to be measured by means of an accurate stop-watch, marking the 50th of seconds.

### § 2. The Expedition. Base Observations before and after the Voyage.

The Base observations before and after the expedition have been made on June 8, June 17, September 27 and October 31 at the Dutch Gravity Base station at De Bilt according to the normal programme 1). On June 8 and 17, five observations were made filling up the interval between the rythmic time-signals of Bordeaux of 8h.01 and 20h.01 Greenwich Time. Four of these observations were made with the usual arrangement of amplitudes and phases, the outer pendulums, Nos. 11 and 13, in opposite phase and with the same amplitude of about 2 cm on the record and the middle pendulum, No 12, free without giving it amplitude. The middle observations on both days were made with the special arrangement for getting data about the middle pendulum, i.e. Nos 11 and 12 in the same phase with amplitudes of resp. 2 cm and 1 cm on the record and No 13 in opposite phase with an amplitude of 3 cm. On September 27, seven observations were made of which Nos 4 and 7 were made with the special arrangement of phases and amplitudes and the others with the usual one. On October 31, eight observations were made, Nos 4 and 5 with the special arrangement and the others with the usual one. The observations of September 27 were enclosed by the rythmic time-signals of Bordeaux of 8h.01 and 20h.01, while those of October 31 were made between the rythmic signals of Paris of 9h.30 and 22h.30 Greenwich Time. The pendulums were mounted in the apparatus in such a way, that the numbers on top of them read from the left side of the apparatus.

As it was possible that variations of the pendulums had occurred during the transportation on the 27th of June from De Bilt to the naval base of Den Helder, the writer resolved to make checking observations in this port, where gravity is known by the land determinations of 1920. On the 28th the apparatus was mounted on board the O 13, and as the ship was still in the dry-dock, it could be levelled accurately and a good check could thus be made on the position on the record of the line of zero-tilt of the swinging-plane. It showed in the same place as in De Bilt. In the evening of the same day, the time-signal of Bordeaux was taken and afterwards a pendulum observation was made. On the next morning the ship left the dock and another observation was made at a short distance away.

At eleven o'clock the submarine got under way for a short trip in the North Sea for making observations in connection with an investigation that had already been begun in 1931. As this investigation will be treated of in a separate report, no details will be given. After making seven dives, corresponding to seven observations, the ship returned in Den Helder on the evening of the next day; the seven dives had been made inside thirty hours! It meant a good record as far as the number of dives in a short time was concerned and it meant a great stress for captain and crew.

Late in the evening of June 30 another observation was made in the harbour and a last one was made early on the next morning. The series was closed by the time-signal of Bordeaux

<sup>1)</sup> Theory and Practice of Pend, Obs. Sea a, p. 25 et seq.

of  $8^h.01$ . So, in total, four pendulum observations had been made in Den Helder in two series of two.

After the end of the expedition, the ship returned in Den Helder on the early morning of August 14 and the writer resolved to use that day for a check on the pendulums. Between the time-signals of Bordeaux of 8h.01 and 20h.01, four pendulum observations were made, regularly distributed over the interval. The next day the apparatus was taken out of the ship and transported to De Bilt.

All the observations in Den Helder have thus been made on board of the submarine and they were made according to the normal programme for sea observations.

### The Voyage.

On July 5, the O 13 left Den Helder for the greater trip to the Atlantic. The ship measured about 700 tons at the surface and 800 tons during submergence. Its staff consisted of

Lieutenant-Commander P. ROUWENHORST, Captain,

Lieutenant G. Koudijs, Executive Officer,

Lieutenant A. J. Krom, in command of the engine-room,

Lieutenant W. J. HOOTSEN, Navigator.

The writer feels sincerely indebted to Captain ROUWENHORST for his efficient cooperation, which has made it possible to realize the complete scientific programme. The great number of dives necessary for the observations, in connection with the long trips between the harbours, must have been a great strain to him and to his officers and crew. I wish thankfully to acknowledge the assistance of the officers during the expedition and the friendly spirit of comradeship in the mess-room that helped so much to obliterate the lack of comfort inherent to submarine voyages on the ocean. Our trip has generally been favoured by fairly good weather, but occasionally rougher sees occurred and the hatches in the lower deck had often to be closed.

During the first twenty-four hours, three dives were made in the North Sea for finishing the investigation that has been mentioned above. These observations will be treated of in another report and so they will not further be mentioned in this publication. On July 8 we arrived at the end of the Channel, near the continental shelf, and here the principal programme of the expedition began. Between this point and our arrival at the first port, Punta Delgada on the island of São Miguel, eleven observations have been made. Their positions may be inferred from the map, where they are marked by the numbers 426—436. The first pair of observations had regard to the shelf, the first being on shallow water at the top of the slope and the second on deep water over the foot.

After arrival in Punta Delgada on the early morning of July 13, an observation was made in the harbour and in the afternoon a second one was made. The series was closed by the evening time-signal of Bordeaux.

After a rest of five days, the trip was resumed; at two o'clock of July 19, the O 13 left for its longest leg of twelve days to Funchal on the island of Madeira. During this trip thirty-one observations have been made of which the positions are found on the map under the numbers 438—468. Station 444 had to be repeated because the course had been irregular during the first observation and so the Eötvös correction could not be determined with sufficient accuracy. Stations 455 and 456 were likewise doubled, this time because the soundings showed an irre-

gular sea-bottom and so it was deemed advisable to make a second observation for diminishing the effect of unknown topographic irregularities.

The crew had a well-deserved rest at Funchal, where the ship stayed from July 31 till August 6. On the first day, two observations were made in the harbour. On August 6 the last leg of the trip began, which took us eight days till Den Helder, where we arrived on August 14. Seventeen observations were made on the first six days. They are indicated on the map by the numbers 470—486. The last two observations were made near the European shelf at the end of the Channel, No 485 over the foot of the slope and No 486 over the top.

The observations have all been made according to the normal programme given on page 24 of "Theory and Practice of Pendulum Observations at Sea". As well as it is possible, the outer pendulums got equal amplitudes in opposite phases and the middle one was set free with no amplitude. The observations were made during half an hour, i.e. four minutes at the beginning and at the end with high paper-speed and only momentary light-interruptions by the chronometers and the intervening time with low paper-speed and half-second light-interruptions by one of the chronometers. For most of the observations, these half-second interruptions were made by the mean time chronometer, because the coincidence-interval for this chronometer had the right length for providing a sufficient number of measuring places for the quantity b (see p. 81 and the plate on p. 84 of Th. a Pr. o. Pend. Obs. a. S.) without giving an unnecessary great number as it would have been the case if these interruptions had been made by the sidereal chronometer with its shorter coincidence-interval.

The pressure of the air during the observations was determined by two aneroids, one belonging to the ship and one brought along from De Bilt. Both were compared in Den Helder before and after the expedition by means of a mercury barometer. The controll did only show fluctuations in the corrections of a few tenths of millimeter. The hair hygrometer of the pendulum apparatus was likewise checked before and after the expedition by means of a psychrometer; the correction had remained steady up to a few percent.

Up to July 10, the rythmic time-signals of Rugby of 9h.55 and 17h.55 Greenwich Time have been used for checking the rates of the chronometers, but for the whole further voyage, the signals of Bordeaux of 8h.01 and 20h.01 were taken. There was never any trouble for getting them sufficiently loud for satisfactory comparizon. The signals were received by the well-known method of putting the break-circuit of one of the chronometers in series with the telephone and by noting down the moments of appearance and disappearance of the signals. Before and after the time-signal, the second chronometer was aurally compared to the other by means of coincidences of the ticks.

The sounding by means of the echo method proved not to be possible when the ship was at the surface. The sending apparatus was situated high up in the sides of the vessel and so the sound was scattered by the waves. Also the sending was directed horizontally and only a small fraction of the energy went downwards. During submergence, however, the receiving microphone was quiet enough to hear the echo, although it was rather weak, and so the sounding during the pendulum observations gave no trouble. The impossibility of getting echos at the surface of the sea was a deception, because the writer had hoped to get a continuous depth-profile for the whole route. In order to get at least some data about the topography near the stations, the soundings were already begun about half an hour before the pendulum observations and they were continued for the same time afterwards. Usually the submergence thus took about one hour and a half and, as the speed during submergence was about four knots, the

soundings extended for every station over some six miles. Incase unexpected things were found, the submergence and the soundings were continued over a longer time.

The soundings were made in the same way as during previous expeditions. The handle of the Fessenden apparatus was pressed down by the radioman at the same moment that he started the stop-watch with his other hand; experiments showed that this ensures the coincidence of both manipulations up to one or two hundredths of a second. The time of the echo was read on the dial of the stop-watch without stopping the indicator. In this way the time-lag connected with stopping was avoided. Each sounding operation consisted of a number of usually ten consecutive soundings of which the mean was taken. The accuracy of the mean echo-time thus obtained may be estimated at two or three hundredths of a second, which corresponds to an accuracy of 15—25 meters for the depth. The sounding operations were made at intervals of a quarter of an hour, corresponding to distances of one sea-mile.

For deducing the depths, the tables 5 and 6, resp. for the N.W. African region and for the Gulfstream Region, of the Tables edited in 1927 by the British Admiralty, have been used. The resulting depth was rounded off to ten meters.

4010 m. 43° 13′.8 N, 19° 24′.0 W. 3980 3770 3800 3920 3960 3910 3880 3920 4160 Station 431. (M.E. 2 miles)	1980 m. 37° 06′.5 N, 33° 33′.7 W. 1990 ,, 1970 ,, 1730 ,, Station 445, (M.E. 1½ miles) 1630 ,, 1370 ,, 1110 ,, 1010 ,, 1110 ,, 1460 ,, 37 10.9 N, 33 43.5 W.
4210 ,, 4220 ,, 43 13.8 N, 19 39.1 W. 4230 ,, 4200 ,, 4120 ,, 4070 ,, 3980 ,, 3850 ,, 43 07.8 N, 19 39.1 W.	3620 m. 38 02.5 N, 36 01.5 W. 3530 ,, 3730 ,, Station 447 (M.E. 1½ miles) 3770 ,, 4250 ,, 4260 ,, 4120 ,, 38 06.1 N, 36 09.3 W.
2510 m. 42 00.7 N, 27 56,5 W. 2710 ,, 2560 Station 456A (M.E. 1½ miles) 2710 ,, 2700 Station 456B (M.E. 1½ miles) 2730 2710 ,, 42 00.3 N, 27 47.5 W.	1720 m. 42 06.3 N, 29 17.8 W. 1930 2320 ,. 2650 ,, Station 455A (M.E. 1½ miles) 2620 2300 ,, Station 455B (M.E. 1½ miles) 2280 ,, 2020 1930 ,, 42 05.7 N, 29 06.6 W.

From the results the mean depth was derived for each pendulum observation over the two miles corresponding to the duration of the observation. These figures are published in the list of results of the next chapter. The positions and the mean errors of the positions are likewise given in this list.

For most of the stations the other soundings did not show much deviation from this mean depth and so it does not appear necessary to publish them. They have been taken into account for the isostatic reduction of the results. For a few stations, however, the additional figures seem worth while publishing. They are given here in the above table, in which the figures of each series refer to spots at a mutual distance of about one nautical mile; as the positions are given of the first and the last sounding of a straight line, the positions of all the depths can be readily derived. The number of the stations corresponding to the series are indicated near the depth that was taken about halfway the observation. The positions are given in tenths of minutes of arc for better indicating their relative positions. The mean error of the absolute position is much larger; it is mentioned in the above lists behind the number of the stations.

The first of the sounding series, corresponding to station 431, has not been given because of irregularities of the depth, but because of the fact that the charts indicate a great depth at this place of about 6000 meters. We have not been able to find this trough, although the submergence, which chanced to fall in the middle of the night, was continued for four hours and a half. If the trough exists, it appears to be elsewhere, unless our own navigation was much more in error than seems to be likely with regard to the data of the position determinations.

The series corresponding to station 445 is interesting, because it indicates a ridge that is not given by the charts. It appears likely that this ridge is a continuation of the elevation of the sea-bottom running southwestwards from Flores, the most western island of the Azores. For a confirmation of this supposition, a further investigation of the area is of course necessary.

The two series of stations Nos 455 and 456 are situated on the Mid-Atlantic ridge north of the Azores. They show irregular topography. The gravity observations have been doubled for these stations in order to lessen the uncertainty that these irregularities bring about in the topographic reduction of the results.

The positions of the gravity stations have been provided by the officers of the ship. The data were discussed and an estimate was accordingly made of the mean error of the positions. The same data were used for determining the east-west component of the current, needed for the computation of the Eötvös effect. The principal figure needed for this correction, the ship's speed with regard to the water, was deduced from the number of revolutions of the screw. This was kept constant during submergence corresponding to a speed of four miles an hour. There was no need to check this speed by pairs of gravity observations on the same spot, one with easterly and one with westerly course in the way this has been done during former expeditions, because the ship had not become so foul that an appreciable change could be expected of the relation of the speed and the number of revolutions of the screw.

The west-east component of the current during the observations and the estimate of its mean error has been given in the list at the end of this chapter. The positions of the stations and their mean error can be found in the list of results of the next chapter. The positions in the harbours of Punta Delgada and Funchal are given with greater precision and so the location of the ship in these harbours may be accurately derived from these figures. These positions are of course given with regard to the normal harbour charts; their absolute accuracy depends on that of the charts.

## § 3. The Computations, the Results and the Mean Errors.

## A. The Computations.

The computations and reductions of the observations have been made according to the methods of §§ 1—5 of Chapter III of "Theory and Practice of Pendulum Observations at Sea". The periods of the fictitious pendulums were determined with the graphical method of page 78, which has proved to give sufficient accuracy and which saves considerable time compared with the computational method of pages 75 et seq. For each fictitious pendulum, four passages of the chronometer-marks through the axis of the record were determined, two at the beginning and two at the end of the observation and this was done also for the marks of the other chronometer.

For the corrections for temperature the constants have been used that have been determined by the writer, assisted by Mr. T. T. Brown, in the Naval Research Laboratory at Washington in January 1932. The writer wishes here to acknowledge the kind support of the Director of this laboratory and of his personnel and the facilities given in connection with this work.

```
Pendulum No 11 C_t = 48.60\ 10^{-7} seconds per degree, ,... No 12 C_t = 50.64 ,... ,... ,... ,... ,... ,... ,... No 13 C_t = 48.32 ,... ,... ,... ,... ,...
```

For the corrections for the effect of the surrounding air, the same constant was used for all the pendulums. It had been determined by the writer in De Bilt, in December 1931, before his departure for the United States.

$$C_{\rm d} = 625\ 10^{-7}$$
 seconds per unit of air-density.

Two difficulties were met with in connection with the computations. The pendulums proved not to have been perfectly stable during the expedition and the rates of the two chronometers have shown greater fluctuations than during previous expeditions. Both facts tend to diminish the accuracy of the results as we shall nearer examine when treating of the mean errors of the results.

Of the rates of the two chronometers, that of the mean time chronometer No 2081 was somewhat more regular than that of the sidereal time chronometer No 212, but on three occasions, i.e. on July 20, on August 7 and on August 11, each time between the signals of 8h.00 and 20h.00, a sudden deviation of the rate of No 2081 of about two seconds daily rate occurred. According to the results of the computations of the pendulum observations, the rate of this chronometer during the observations had been about normal and so the conclusion was drawn that the abnormal figures were brought about by sudden jumps of the chronometer of a whole second. This conclusion was further confirmed by the experience with the same chronometer during an expedition of the French Navy in the autumn of 1933. Besides the chronometers Nos 2081 and 212 this last expedition was equipped with two other chronometers and they could be compared with an accuracy of a thousandth of a second by means of a recording apparatus. In this way continuous determinations of the relative rates were possible over short intervals and this allowed to recognize indubitably the cause of the irregularities of chronometer No 2081 as sudden jumps of a second.

According to this conclusion, the three abnormal rates of No 2081 were corrected by an amount of two seconds, but to the value that thus was found, a smaller weight was given than to the others.

The writer tried to improve the agreement of the values for the means of the two reduced fictitious pendulum periods as given by the two chronometers, by applying an interpolation formula for the rates, which expresses the rate during a certain observation in the rates over the three consecutive time-signal intervals before, during and after the observation. This was, however, a failure as the agreement usually got worse. So, for the final computations, the rate was simply taken from the time-signal interval in which the observation was made. Only incase the observation was close to a time-signal, an interpolation of the rates of the contiguous intervals was made. The agreement of the values of the mean periods given by the two chronometers can be checked by the list at the end or this chapter of the differences v for all the stations of the expedition.

For deducing the final value of the mean period for a station, the values given by the two chronometers have to be combined. This has been done by giving them weights in inverse ratio to the fluctuations of the rates in the three time-signal intervals before, during and after the observation.

#### B. The Results for the Base Observations.

The computation of the base observations in De Bilt gave the following results for the reduced periods of the two principal pendulums Nos 13 and 11 and for their difference d

Date	$T_{13}$	T <sub>11</sub>	d
June 8, 1932 June 17, 1932	0.5031502 0.5031504	0.5031483 0.5031491	19
Mean before Exp.	0.5031503	0.5031487	16
Sept. 27, 1932 Oct. 31, 1932	0.5031494 0.5031499	0.5031427 0.5031428	67 71
Mean after Exp.	0.5031496	0.5031427	69

This shows that pendulum No 13 has been fairly stable during the expedition but that pendulum No 11 has varied seriously. Under these conditions, the observations made at Den Helder before and after the trip are valuable. When we reduce the results from Den Helder to De Bilt in order to make them more easily comparable to the above figures, which can be done by means of the value for the difference of gravity found in 1920 by the land observations <sup>1</sup>), we find for the observations before the expedition:

Date	$T_{13}$	$T_{11}$	d
June 28/29, 1932 June 30/July 1, 1932	0.5031510 0.5031501	0.5031502 0.5031481	8 20
Mean before Exp.	0.5031505	0.5031491	14

<sup>1)</sup> Observations de Pendule dans les Pays Bas", 1913-1921, Publ. of the Netherlands Geodetic Commission, Waltman, Delft, 1923.

This is in good agreement with the mean values found in De Bilt before the trip. For the observations made in Den Helder after the return of the expedition we find, if we reduce them likewise to De Bilt:

August 14, 1932, 
$$T_{13} = 0.5031486$$
,  $T_{11} = 0.5031446$ ,  $d = 40 \times 10^{-7}$  sec.

The result for pendulum No 13 is in passable agreement with the value found afterwards in De Bilt, but for pendulum No 11 there is a great difference. It appears that a good part of the change of this pendulum must have occurred during the transportation to De Bilt, although this has been done carefully and no accident happened.

The values found in Den Helder for the difference d of the two pendulums before and after the trip are in good harmony with the differences found during the trip. These differences are given in the list of results of this chapter. They show a gradual increase from a value of less than  $20 \times 10^{-7}$  sec in the beginning to a value of nearly  $40 \times 10^{-7}$  sec at the end. This is also clearly shown by the mean values of d for the first twenty stations, for the second twenty stations and for the last twenty-one stations. These means are respectively 20, 25 and  $33 \times 10^{-7}$  seconds. So there seems reason to suppose that the change of the pendulums during the trip occurred gradually.

Although this result diminishes the uncertainty adhering to pendulum No 11, it nevertheless does not take it quite away and so the writer has preferred to eliminate this pendulum from the computation of the gravity results of the expedition. The results have, therefore, been exclusively computed with the data for pendulum No 13. The effect of this decision on the accuracy of the result will be examined afterwards.

For the base value of pendulum No 13 at De Bilt before and after the trip, it seems indicated to take the means of the determinations at De Bilt and at Den Helder. This gives

```
Before the expedition T_{13} = 0.5031504
After the expedition T_{13} = 0.5031491
```

The fact that we found that the differences of the pendulum periods have changed gradually during the expedition, has given rise to assume that the period of pendulum No 13 has likewise changed gradually from the first to the second value. Its period at De Bilt has, therefore, been put at the following values

```
For stations Nos 426—445, T_{13} = 0.5031502

... Nos 446—465, T_{13} = 0.5031498

... Nos 466—486, T_{13} = 0.5031494
```

If the mean value had been taken for all the stations, this would only have meant a slight difference for the gravity results.

Besides the periods of the principal pendulums at De Bilt, we likewise need for the computations their differences from the period of the middle pendulum, no 12. For this quantity the following values, expressed in  $10^{-7}$  seconds, have been found in De Bilt before and after the expedition

June 8/17, 1932, 
$$T_{13} - T_{12} = 48 - 2.32 \, t^{\circ}$$
  $T_{11} - T_{12} = 34 - 2.04 \, t^{\circ}$   
Sept 27/Oct 31, 1932,  $T_{13} - T_{12} = 77 - 2.32 \, t^{\circ}$   $T_{11} - T_{12} = 8 - 2.04 \, t^{\circ}$ 

The second terms of these expressions arise from the differences of the temperature constants of the new pendulums;  $t^{\circ}$  represents the temperature.

We see that pendulum No 12 has likewise varied during the expedition. According to the same considerations as above, the following formulas have been used

For stations Nos 426—445, 
$$T_{13}-T_{12}=52-2.32\ t^{\circ}$$
,  $T_{11}-T_{12}=30-2.04\ t^{\circ}$  , Nos 446—465,  $T_{13}-T_{12}=60-2.32\ t^{\circ}$ ,  $T_{11}-T_{12}=22-2.04\ t^{\circ}$  , Nos 466—486,  $T_{13}-T_{12}=68-2.32\ t^{\circ}$ ,  $T_{11}-T_{12}=14-2.04\ t^{\circ}$ 

As the variations of the middle pendulum practically only affect the differences d of the periods of the fictitious pendulums and not their mean value, the accuracy of the gravity results is not affected by errors of these quantities.

The results of the computations for all the stations are given in the list at the end of this chapter. Like those of former expeditions, they are based on a value of g for De Bilt of 981.268. For the stations Nos 437, 455, 456 and 469, where two observations have been made, the results are given separately, but in the synopsis of results of all the expeditions in the next chapter, they have been combined in one value and, accordingly, the position for those stations, where the two observations have been made some distance apart, were combined in a mean position.

The comparizon of the two values at the stations Nos 437 (Punta Delgada) and 469 (Funchal) shows differences of 9 and 7 milligal, although the observations were made at the same spot. These differences are rather great, but they don't much exceed what may be expected when we take into account that in both cases the rates of the chronometers were not steady. The mean errors computed for those stations likewise agree fairly well with the amount of the differences.

For the stations Nos 455 and 456 the differences between the two values are still greater, i.e. 9 and 13 milligal, but in both cases the two observations are about two miles apart and the topography of the sea-bottom is irregular and so differences may be easily understood. The deviations, moreover, go in the sense that may be expected; the smaller gravity values have been found over the greater depths.

The results of the expedition will be examined and discussed in Chapters IV et seq together with those of the other expeditions.

#### C. The Mean Errors of the Results.

For the general aspects of the question how to deduce the mean error of gravity observations at sea, the writer may refer to pages 61 and 98 et seq of the first volume. It was found there that the mean error of the mean of the two fictitious pendulum-periods at a station may be computed by taking the root of the sum of the squares of half of the mean deviation of the difference d of these periods and of half of the mean value of the difference v between the two values of these periods as they are given by the two chronometers. Neglecting the mean error of the values of the pendulum-periods at the base-station, the above mean error was also adopted for the difference of the mean periods at the station and at the base-station and the mean error in milligal of the gravity result was accordingly found by multiplying this mean error with 0.39.

For the results of this expedition, the method had to be modified in order to take into account the special circumstances. Firstly, the results have been deduced from one fictitious pendulum only, instead of from two, and so we have to introduce half of the square of the mean deviation of the difference d instead of the square of half of this mean deviation. This mean deviation has been deduced separately for the first twenty stations, for the second twenty stations and for the last twenty-one stations and in this way the following values have been found: 7.5, 4.0 and  $5.4 \times 10^{-7}$  seconds. For the computation of the mean errors, the mean value  $5.6 \times 10^{-7}$  seconds was adopted. The mean deviation of d has not been derived from the series as a whole, because the second fictitious pendulum had varied and so d had gradually changed. This change would cause an appreciable increase of the figure for the mean deviation if this would be derived from the whole series, and so we should not have obtained a figure that would be representative for the behaviour of the first fictitious pendulum used for the computations.

A second modification had to be made for taking into account that the first fictitious pendulum had also undergone a small variation during the expedition. This causes some uncertainty of the period of this pendulum at the base-station and so the difference of the periods at the station and at the base-station is affected. In consequence of this, the square of the mean error of this difference had to be increased by the square of the uncertainty of the base-station value. Referring to the values mentioned in the previous paragraph of this chapter, the uncertainty has been estimated at  $5 \times 10^{-7}$  seconds and so the square of the above mean error has been increased by 25.

A last modification was made with regard to the uncertainty of the rates of the chronometers. This uncertainty has formerly been taken into account by adding the square of half of the mean value of v. As, however, the chronemeter-rates were at some times more regular than at others, it was preferable to make a difference for values obtained in regular and in irregular periods of the chronometers. This was realized by adding the square of half of the value of v of the observation itself instead of the square of half of the mean value of v over all the observations. By this method, the effect of the uncertainty of the rates is probably over-estimated because we thus assume that the values given by both chronometers have been combined with equal weights, while in reality the value given by the most steady chronometer did receive a greater weight, and this reduces the uncertainty of the result.

Resuming, the mean error of the gravity result has been derived by means of the following formula

$$m_g = 0.39 \sqrt{\frac{1}{2} \times 5.6^2 + 25 + \frac{1}{4} v^2} = 0.39 \sqrt{41 + \frac{1}{4} v^2}$$

## D. The Mean Error of the Gravity Results reduced to Sea Level.

Referring to what has been said about this subject on page 98 of the first volume, the error of the reduction of the gravity result to sea-level may be neglected and we have only to take into account the error of the correction for the Eötvös effect, caused by the uncertainty of the W-E component of the current. This uncertainty is mentioned for each station in the list of this chapter. Multiplying it by 7.5  $\cos \varphi$ , we find the error of the Eötvös correction and, combining this value with the value of  $m_g$  by taking the root of the sum of the squares, we obtain the mean error of the gravity result reduced to sea-level.

This mean error has been derived for all the observations of the expedition. It is mentioned in the list of this chapter behind the value of the gravity result itself. It is likewise given in the synopsis of all the gravity results of the next chapter, but for those stations where two observations have been made, the mean error of the combined result is mentioned.

## E. List of Results of the Expedition of Hr. Ms. O 13 in the Atlantic.

The data concerning the observations and the computations that are of interest to the reader or critic have been put together in the following list. The first column gives the number of the station; this number coincides with the number in the list of the next chapter. The second column gives the dates and harbour-names, the third the depth in meters at which the observation has been made, the fourth the change of the temperature in the apparatus during the half hour of the observation, the fifth the difference d of the reduced periods of the two fictitious pendulums, the sixth the difference d of the mean of the fictitious pendulum-periods as it is given by chronometer No 212 minus the mean of these periods as it is given by chronometer No 2081, the seventh the d0 component of the current in nautical miles, the eighth the estimate of its mean error, likewise in nautical miles, the ninth the gravity result reduced to sea-level, the tenth its mean error in milligal, the eleventh the normal gravity for the station as it is given by the formula of Cassinis mentioned on page 10, and the twelfth the unreduced anomaly, i.e. the difference of the gravity result reduced to sea-level minus the value of normal gravity d1).

It may be repeated here that the gravity results are based on a value of g at the base-station of De Bilt of 981.268. For those not familiar with the navigational unity of distance, it may be mentioned that the nautical mile is 1853 meters.

 $<sup>^{1}</sup>$ ) In the lists of results of the previous expeditions in the first volume, the factors of the differences U of the pendulum-periods which were used for the computations, have been mentioned. This has been omitted here, because it has only a meaning when the pendulum-periods are stable and when thus the effect of the middle pendulum on the results can be checked. This was not the case for the above expedition.

# Results of the Gravity Observations 0/b Hr. Ms. O13 in the Atlantic, 1932.

	Date 1932	Depth	<u> </u>	d	U	Cur		,			
Nr.		Observ.	Change Temp.		<u> </u>	W-E	Mean error	go	mg mgal	γ.,	A mgal
	Harbours	m		10	sec	naut.	miles				
426	8 July	23	+0.07	24	<u>–16</u>	0.0	0.2	980.945	4	980.930	+ 15
427	8 .,	28	+0 07	19	+14	0.0	0.2	980.804	4	980.876	- 72
428	9 "	33	+0.15	23	-38	0.0	0.2	980.825	8 .	980.752	+ 73
429	10 ,,	33	+0.03	11	13	-0.1	0.2	980.642	4	980 590	+ 52
430	10 "	28	+0.12	19	+16	-0.4	0.2	980.557	4	980.536	+ 21
431	11 "	28	+0.15	15	- 8	00	03	980.520	3	980.470	+ 50
432	11	28	+0.25	22	-21	0.0	0.3	980.431	5	980.386	+ 45
433	12 .,	28	+0.02	15	+14	-0.2	0.2	980.257	4	980.248	+ 9
434	12	28	+0 09	9	+17	-0.2	0.2	980.189	4	980.17 <del>4</del>	+ 15
435	12 .,	28	+0.19	12	+ 2	-0.3	0.2	980.139	3	980.103	+ 36
436	13 "	28	-0.02	17	- 8	-0.3	0.2	980.029	3	980.035	- 6
	n n 14-		[								
437A	P. Delgada 13 July	2	+0.19	21	-26	0.0	0.0	980.129	6	979.981	+148
437B	13	2	+0.10	18	-16	0.0	0.0	980.138	4	979.981	+157
438	19 "	28	+0 05	16	+15	-0.2	02	979.951	4	979.940	+ 11
439	20 ,,	28	+0.04	12	-15	0.0	0.1	979.853	4	979.828	+ 25
440	20 .,	28	+0.12	33	- 3	0.0	0.1	979.785	3	979.750	+ 35
441	21 .,	28	+0.06	32	-19	0.0	0.1	979.817	4	979.784	+ 33
442	21	28	+0 09	28	- 7	-0.8	0.2	979 854	3	979.818	+ 36
443	21 "	28	+0.06	36	+ 5	-0.8	0.2	979 870	3	979.848	+ 22
444	22	28	+0 08	28	+27	-0.2	0.2	979.935	6	979.884	+ 51
445	22	28	+0.12	18	-25	0.0	0.2	979.977	6	979.929	+ 48
446	22	28	+0.01	24	+ 4	0.0	0.2	980.000	3	979.972	+ 28
447	23 .,	28	+0.01	27	25	-0.5	0.2	980.036	6	980.009	+ 27
448	23 "	33	+0 07	20	-34	0.2	0.2	980.138	7	980 103	+ 35
449	23 .,	28	+0.06	24	- 4	0.0	0,2	980.191	3	980.176	+ 15
450	24 "	28	0.00	27	-22	0.0	0.2	980.293	5	980.266	+ 27
<b>4</b> 51	24 "	28	+0.03	25	31	0.0	0.2	980,389	7	980.354	+ 35
452	24 "	28	+0.01	22	-10	-0.2	0.2	980.424	3	980.382	+ 42
453	25 "	28	0.00	30	+ 9	-0.2	0.2	980.391	3	980 382	+ 9
454	25 "	28	+0.14	32	-10	-0.2	0.2	980.408	3	980.375	+ 33
					!			<u> </u>			1

	Date 1932	D: 4		,		Cur	rent				
Nr.	Date 1932	Depth Observ.	Change Temp.		<i>v</i>	W—E comp.	Mean	$oldsymbol{g}_{\circ}$	mg mgs!	γo	A
	Harbours	m	remp.	10-7	sec.	naut.			mgal		mgal
455A 455B	26 July 26 "	28 28	-0.04 -0.01	23 30	$\begin{vmatrix} -2 \\ +13 \end{vmatrix}$	+0.2 +0.2	0.2 0.2	980.398 980.407	3 4	980.368 980.368	+ 30 + 39
456A 456B	26 26	28 28	0.00 +0.02	12 34	+31 +20	+0.4 +0.4	0.3 0.3	980.400 980.387	7 5	980.360 980.360	+ 40 + 27
457	26	28	+0.06	30	+26	+0.4	0.3	980.381	6	980.339	+ 42
458	27 "	28	-0 02	20	- 7	+0.2	0.2	980.323	3	980.282	+ 41
459	27 .,	28	+0.11	20	_ 2	+0.2	0.2	980.25 <b>4</b>	3	980.226	+ 28
460	28 "	28	-0.01	26	+ 8	+0.2	0.2	980,102	3	980.0 <del>9</del> 6	+ 6
461	28 "	28	+0.06	31	+30	0.0	0.3	980.052	7	980.001	+ 51
462	28	28	+0.06	30	+34	+0.2	0.2	979.958	7	979.915	+ 43
463	29 "	28	+0 04	18	+ 6	+0.2	0.2	979,801	3	979.817	- 16
464	29 "	28	+0.09	27	_ 8	+0.3	0.2	979.717	3	979,724	- 7
465	30 "	28	+0.03	27	+17	+0.3	0.2	979.613	4	979.636	- 23
466	30 "	28	+0.10	40	<b>–</b> 6	+0.4	0.2	979.603	3	979.609	- 6
467	30 "	28	+0.04	33	- 4	+0.6	0.2	979.632	3	979.585	+ 47
468	31 "	28	-0.04	26	+35	+0.8	0.3	979.642	7	979.562	+ 80
4	Funchal										
469A 469B	31 July 31 "	2 2	+0.18 +0.15	43 40	-13 -13	0.0	0.0	979.775 979.782	4 4	979,548 979,548	+227 +234
470	6 Aug.	28	+0.10	42	-21	0.0	0.2	979 562	5	979.564	- 2
47 i	6 "	28	-0 06	24	+11	0.0	0.2	979.586	4	979.584	+ 2
472	7 "	28	+0.03	26	+ 7	0.0	0.2	979.565	3	979.606	- 41
473	7 "	28	+0.13	40	+21	0.0	0.2	979 674	5	979.692	- 18
474	7 "	28	0.00	32	+10	0.0	0.2	979.765	3	979.781	- 16
475	8 "	28	-0.02	28	+ 8	0.0	0.2	979.994	3	979.875	+119
476	8	28	+0.09	29	-12	0.2	0.2	979.901	4	979.958	<b>– 57</b>
477	8 "	23	0 01	28	+14	0.2	0.1	980.013	4	980.047	- 34
478	9 "	28	0.03	35	+19	-0.2	0.1	980.106	4	980.139	- 33
<b>4</b> 79	9 "	28	+0.07	39	+26	-0.3	0.1	980.218	6	980.243	<b>– 2</b> 5
480	10 "	28	+0.01	32	-19	-0 2	0.1	980.335	4	980.342	- 7
481	10 .,	28	+0.02	36	- 7	0.0	0.2	980.537	3	980.414	+123
482	10 "	28	+0.13	32	+14	+0.1	0.1	980.457	4	980.520	- 63
483	11 "	28	0.00	38	<b>-42</b>	+0.1	0.1	980.613	8	980.602	+ 11
484	11 "	28	+0.08	32	13	+0.1	0.1	980.686	4	980.680	+ 6
485	11 "	28	+0.02	32	+ 3	+0.2	0,1	980.765	3	980 783	- 18
486	12 "	28	-0.02	36	<b>– 5</b>	+0.2	0.1	980.920	3	980.876	+ 44
			<u> </u>								

## CHAPTER III:

## Isostatic Reduction of the Results.

## § 1. The Reductions.

Vol I of this publication contains the results for all the expeditions up to the year 1930, including in total 425 stations. The previous chapter gives them for the 61 stations of the expedition in the Atlantic of 1932. The anomalies in these lists may be considered as free-air anomalies; they have been obtained by reducing the gravity to sea-level and by taking the difference with regard to the value of normal gravity as it is given by the internationally adopted formula of Cassinis:

$$\gamma_0 = 978.049 \ (1 + 0.0052884 \ \sin^2 \varphi - 0.0000059 \ \sin^2 2\varphi).$$

For drawing conclusions from these results, it is necessary to reduce them isostatically, by preference according to different methods, and eventually also according to the method of Bouguer. This has been done and the results are given in the list of this chapter.

The isostatic reductions have been made at the Bureau of the U.S. Coast and Geodetic Survey, save those of the last sixty-one stations that have been computed in Holland. Sincere thanks are due to the Coast and Geodetic Survey for the facilities that were given with regard to these reductions and especially for the disinterested way in which this service has been willing to make the reductions of the first two hundred stations without any expense to the Netherlands Commission. Thanks are also due to Mr. Clarence H. Swick, under whose supervision the reductions have been made. The reduction of station No 35, Sevilla, was kindly provided by Col. Sans Huelin of the "Instituto Geográfico y Cadastral".

For all the stations the reductions were first made according to the method of Hayford and Bowie, as it is in use at the Coast and Geodetic Survey, i.e. by dividing the Earth in the system of zones belonging to this method and by computing for these zones the effect of the topography and of the compensation on the gravity at the station. The compensation is assumed to be local, that is to say, the compensation is supposed to be in the same vertical as the topography. It is assumed to be equally distributed over a depth of 113.7 Km below sea-level. For all the stations subsequent to No 195, zone O has been divided into two halves, an inner ring and an outer ring. This was done because this zone is rather broad and so the effect of the attraction of the compensation differs considerably from the inside towards the outside of the ring. The taking into account of a mean elevation over the whole zone thus gives slight errors and this has been taken away by the division into two parts. For the computation of the effect of the topography of this zone, this was not necessary as the corresponding error is much

smaller in this case and so the effect of the topography was derived from the mean elevation for the whole zone.

The reductions for the last sixty-one stations have been made in Holland according to the same methods of the U.S. Coast and Geodetic Survey. As, however, the elevations and depths of the maps, principally the N. Atlantic part of the Bathymetric Map of the Oceans of Monaco, had been read in meters, the effect of the topography was easier to compute by means of the general attraction-tables of Cassinis and Dore than by the tables of the C. and G.S. For the densities the American values were adopted, 2.67 for the land-compartments and 1.64 for the sea-compartments. For the same reason, the combined effect of topography and compensation for the zones 18—1 was computed with the corresponding table of Heiskanen from his paper in the "Bulletin Géodésique" No 30 (1931). For the computation of the effect of the compensation of the zones A—O, the factors were used, that the C. and G.S. had kindly communicated to the writer. For these stations, zone O was divided again in two parts and the effect of the topography was also separately computed for these two parts.

The data for all the Hayford-Bowie reductions are put together in the tables that are added in an enveloppe to this publication. 1) The data for the zones A—O, i.e. the zones from the station up to a distance of 166.7 km, are given separately from the data for the zones 18—1 that cover the remainder of the Earth's surface.

In the tables for the zones A-O the first column gives the mean elevation in meters for each zone, the second the effect on the gravity in 0.1 milligal caused by the topography of the zone and the third the effect in 0.1 milligal caused by the compensation of the zone. The mean elevations of the zones have been derived from the real elevations of the different land compartments of the zone and from negative figures for the sea compartments that are found by multiplying the depths of these compartments in meters by the factor 0.615. In this way all these elevations, multiplied by the density of the crust 2.67, represent the mass pro surface-unit that corresponds to the topography.

For the zones 18—1, only one figure is given for each zone, viz. the combined effect in 0.1 milligal of the topography and the compensation.

The data for the zones A—O of the first 425 stations are found on pages 1—36 of the enveloppe, those for the numbered zones on pages 37—47, those for the zones A—O of stations 426—486 on pages 48—52 and those for the zones 18—1 of these last stations on pages 53—54. The corrections given in these tables have the sign of the attraction exerted by the topographic or compensating masses, that is to say, for correcting the gravity of the station for those effects we have to subtract these corrections from the gravity of the station.

For those stations where two observations have been made a few miles apart, the reductions have regard to the first of the two stations as they were mentioned in the lists of the expeditions in the first volume. The data for the second positions were not considered important enough for complete publication, but we shall presently, in § 3, consider the results of the reductions for both positions of these pairs and compare the corrected values of gravity.

i) During the printing of this report, news was received from the Director of the Coast and Geodetic Survey that slight errors had been discovered in the way in which the effects of the topography and of the compensation had been separated for a few of the inner zones but that the sum of the two effects was not involved. This implies, however, errors in the effect of the topography and, therefore, errors in the Heiskanen and regional anomalies, which are based on these data. If necessary a list of corrections will be afterwards issued.

The totals of the corrections for the zones A—O and 18—1 of each station, i.e. the sums of the columns of the tables, are given in the list of this chapter. The first figure in that list after the data regarding position and sea-depth of the station, is the total effect of the topography of the zones A—O, the second figure gives the total effect of the compensation of these zones and the third gives the combined effect of the topography and the compensation of the zones 18—1.

The figures of the isostatic reductions according to the Hayford-Bowie method have provided the base for the isostatic reductions of the results according to two other methods, that of Heiskanen as it is published in the Bulletin Géodésique No 30 (1931), and that of the writer as it is published in the Bulletin Géodésique No 29 (1931). The Bouguer reductions of the results have likewise been made by means of these figures.

The method of Heiskanen assumes local compensation of the topography according to the principle of Airy; the compensation is realized by roots at the lower boundary of the crust, which immerge in the substratum. The substratum is supposed to have a density that is 0.6 greater than that of the roots. In this way the root is the enlarged image of the topography on a scale 2.67/0.6 = 4.45.

The Heiskanen reduction has been made for a normal thickness of the crust, corresponding to zero topography, of 40 km, which is the smallest value for which the tables of Heiskanen in the above number of the Bulletin Géodésique have been compiled. This differs not much from the value that the writer thinks to be the most likely. For the deeper parts of the Netherlands East Indian seas, he would be inclined to estimate it at some twenty-five kilometers and as the mean elevation of this area may be put at a few thousand meters below sea-level, this corresponds in the system of Heiskanen approximately to T = 40 km.

The reductions have been made according to the following schedule. The mean elevation H of the zones A-J was determined from the formula

$$H = 0.010 E + 0.023 F + 0.047 G + 0.098 H + 0.286 I + 0.536 J$$

which follows from the ratio of the areas of the different zones. The areas of the zones A-D are so small in proportion to the others, that their elevation does not perceptibly affect the mean elevation.

By means of the tables on pages 140-145 of Bulletin Géodésique No 30 the corrections for the compensation of the zones A-O were deduced, but two points had to be observed. First the sign of the corrections was reversed according to a different assumption about the sign, and secondly the negative elevations were multiplied by the factor 1/0.615 = 1.626 because Heiskanen arranged the tables according to the real depths in meters, and not according to these depths multiplied by 0.615, as it has been adopted for this publication in accordance with the system of the Coast and Geodetic Survey.

For the stations with a higher number than 195, zone O has been divided into two parts, and so new tables were necessary for the computation of the corrections for these parts. Dr. Heiskanen has been kind enough to provide these tables. They are given on a separate sheet in the accompanying enveloppe of tables.

The tables on pages 148—150 of B.G. No 30 for the secondary effects of the elevation of the station and of the curvature of the Earth, have been supplemented with a few further values for greater depths.

For the determination of the combined corrections for topography and compensation of the zones 18-13, the tables of pages 146 and 147 of B.G. No 30 have been used, but this was complicated by the fact that the Hayford-Bowie reductions don't give direct indications about the elevations for the zones. The only figures given by the tables are the combined corrections for topography and compensation. Although it was possible to derive at once from these corrections the heights in feet and to transpose these heights in meters, the shorter way was chosen to enter immediately the tables of pages 146 and 147, in the column of F, with the values of the Hayford-Bowie corrections and to take from the other column the values of the Heiskanen corrections.

For the zones 12-1 new formulas have been derived. The depth-dimension t of the root depends on the elevation of the topography H in the following way

$$t = \frac{2.67}{0.6} \times H = 4.445 H$$

This formula is likewise valid for sea-compartments if we substitute for H a negative value equal to 0.615 times the real depth.

For a crustal thickness  $T=40~\mathrm{Km}$ , we find for the depth of the centre of gravity of the compensation below sea-level

$$T + \frac{1}{2}t = 40 + 2.222 H$$

and for the distance between the centres of gravity of the topography and of the compensation1)

$$\frac{1}{2}H + T + \frac{1}{2}t = 40 + 2.722 H$$

For the Hayford-Bowie method, the centre of gravity of the compensation lies  $56.85~\rm Km$  below sea-level and so the distance between the centres of gravity of the topography and the compensation is here 56.85~+~0.500~H.

As the combined effect of the topography and of the compensation for distant zones may be put proportional to this distance, we find this combined effect for the method of Heiskanen by multiplying the value of this combined correction for the Hayford-Bowie method by the ratio

$$F = \frac{40 + 2.722 \, H}{56.85 + 0.500 \, H} = 0.71 + 0.042 \, H + \dots$$

So all the corrections for the zones 12-1 have to be multiplied by this factor F. The second term, however, of this factor depends on H and we have no direct indication about the elevation of each zone. We can derive H from the Hayford-Bowie correction and substitute this value, in the above formula. Indicating the corrections for the Hayford-Bowie system bij  $C_{12}$ ,  $C_{11}$ ,.....  $C_{1}$  we obtain

Zone 12 
$$H = -\frac{C_{12}}{32.8}$$
  $F_{12} = 0.71 - 0.0013 \ C_{12}$   
Zone 11  $H = -\frac{C_{11}}{26.2}$   $F_{11} = 0.71 - 0.0016 \ C_{11}$   
Zone 10  $H = -\frac{C_{10}}{19.7}$   $F_{10} = 0.71 - 0.0021 \ C_{10}$   
Zone 9  $H = -\frac{C_{9}}{13.1}$   $F_{9} = 0.71 - 0.0032 \ C_{9}$ 

<sup>1)</sup> For sea-compartments this formula is not strictly true, but for our purpose the error may be neglected.

Zone 8 
$$H = -\frac{C_8}{13.1}$$
  $F_8 = 0.71 - 0.0032 C_8$   
Zone 7  $H = -\frac{C_7}{6.6}$   $F_7 = 0.71 - 0.006 C_7$   
Zone 6  $H = -\frac{C_6}{5.9}$   $F_6 = 0.71 - 0.007 C_6$   
Zone 5  $H = -\frac{C_5}{5.2}$   $F_5 = 0.71 - 0.008 C_5$   
Zone 4  $H = -\frac{C_4}{3.9}$   $F_4 = 0.71 - 0.011 C_4$   
Zone 3  $H = -\frac{C_3}{3.3}$   $F_3 = 0.71 - 0.013 C_3$   
Zone 2  $H = -\frac{C_2}{2.0}$   $F_2 = 0.71 - 0.02 C_2$   
Zone 1  $H = -\frac{C_1}{0.3}$   $F_1 = 0.71 - 0.1 C_1$ 

and if the zones 1-6 have been taken together, as this is often the case

Zone 1-6 
$$H = -\frac{C_{1-6}}{20.6}$$
  $F_{1-6} = 0.71 - 0.0020 C_{1-6}$ 

By means of these factors it is easy to derive the Heiskanen corrections from the Hayford-Bowie corrections for these zones.

The corrections for all the zones have been derived from the mean elevation of each zone. This is correct for the compensation-correction according to the method of Hayford-Bowie, but for the Heiskanen method it is, strictly speaking, not allowed and so we have to apply corrections to the values that have been deduced. In an article in the Bulletin Géodésique, no. 38, "La Réduction Isostatique selon l'Hypothèse de Airy", the writer has investigated this question and deduced a formula for the correction to be applied. For each zone it is proportional to the square of the standard deviation of the elevation, i.e. to the mean value of the square of the deviations from the mean elevation in the zone. The factors with which this square has to be multiplied, are different for each zone and they also depend on the mean elevation of the zone. In the above article a table is given for these factors incase the Heiskanen reduction is based, as it is the case for this publication, on a normal thickness T of the crust of 40 km.

This correction has been applied to the stations from No.196 up to No. 425, i.e., to all the stations in the Netherlands East Indies of the expeditions of 1929 and 1930. On pages 55 et seq of the enveloppe of tables, the values of the square of the standard deviation is given for all those zones where the correction was not negligible. From these values the corrections were derived by means of the above table and these corrections have been applied to the total values for the Heiskanen corrections used for the computation of the anomalies and mentioned in the table of this chapter. The corrections seldom exceeded an amount of two or three milligal and mostly they were one milligal or less. This is remarkable, because the Netherlands East Indies have an irregular topography and so the effect must be greater here than in most other areas. We may conclude that this correction may be neglected incase no great accuracy is needed and this is evidently the case for the gravity observations at sea, because the mean error of the determinations at sea precludes an accuracy greater than a few milligal.

The totals of the Heiskanen corrections for all the zones together have been inserted in the list of this chapter in two columns behind the Hayford-Bowie corrections, the sum of the corrections for the compensation of the zones A-O in the first column, and the sum of the combined corrections for the topography and the compensation of the zones 18-1 in the second column.

The method of the writer assumes regional compensation, i.e. the compensation is supposed to be spread out over a greater area than the topography to which it belongs. The horizontal distribution is chosen corresponding to the assumption that the topography may be considered as a load on the crust and that this load brings about an elastical deformation of the crust. The corresponding sinking of the crust brings about a displacement of the substratum by lighter crustal material and likewise a displacement in the crust of each layer by the adjacent layer above it. According to this view-point, the horizontal distribution of the compensation is chosen proportional to the sinking of the crust and in vertical sense it is supposed to be concentrated for the greatest part at the lower boundary of the crust and for a smaller part in the crust, depending on the assumptions about the vertical gradient of the density in the crust.

The thickness of the crust is supposed to be uniform, i.e. everywhere twenty-five kilometers; it is true that many indications point to its being thicker in the continents than under the oceans, but the assumption of differences in thickness offers complications. For the reduction of the gravity observations of this publication, the following assumptions have been made regarding the densities. The density of the substratum has been put at 3.30, the density of the crust at the surface at 2.67. In the lower layers of the crust a slight increase of density has been assumed corresponding to the compression by the weight of the higher layers. The density-increase has been put at  $3.5 \times 10^{-9}$  per gram/cm<sup>2</sup> of vertical pressure, which, according to more recent figures, is somewhat too high 1), but as the effect on the reductions of a change of this figure is small and as the assumptions cannot be considered as more than hypothetical, it was not thought necessary to repeat the reductions with a new figure.

The consequence of our assumption is a gradual increase of density in the crust of 0.073 from the surface to the bottom. This is about 12 percent of the total increase of 0.63 between the surface density of 2.67 and the substratum density of 3.30, and so we get 88 percent of the compensation concentrated at the lower boundary of the crust and 12 percent distributed over the crust.

In the article in the Bulletin Géodésique, No 29, in which the method is set forth, factors s have been deduced with which the corrections according to the Hayford-Bowie method must be multiplied for obtaining the corrections according to this new method. These factors have been derived for a few different assumptions. The factors  $s_1$  have regard to the assumption that the compensation is concentrated at the lower boundary of the crust and the factors  $s_2$  to the assumption that it is uniformly distributed over the crust. It is easy to deduce from these two sets the factors for our assumption; we find them by means of the formula

$$s = 0.88 \, s_1 + 0.12 \, s_2$$

<sup>1)</sup> JEFFREYS "The Earth", 2nd Edition, p. 102, where a value is given for the reciprocal of the bulk-modulus of  $1.9 \times 10^{-9}$  for granite at about the same depth. This value was determined by the investigations of L. H. ADAMS, E. D. WILLIAMSON and R. E. GIBSON,

In this way we obtain the following set of factors for all the zones:

Zone $A$ — $F s =$	0 Z	Zone	$18  \mathrm{s} = 1.0$	)2	Zone	$9 \ s = 0.42$
G = s = s	0.1	,,	$17 \ s = 0.9$	91	,,	$8 \ s = 0.42$
H = s = s	0.1	* *	$16 \ s = 0.8$	31	,,	$7 \ s = 0.42$
$_{,,}$ $I$ $s=$	0.14	,,	15 $s = 0.6$	56	,,	$6 \ s = 0.42$
J = s = 1	0.26	,,	14 $s = 0.5$	58	,,	5 s = 0.42
K = s = s	0.37	,,	$13 \ s = 0.5$	50	,,	4 s = 0.42
L s =	0.59	,,	12 $s = 0.4$	12	,,	3 s = 0.42
M = s = s	1.11	,,	11 $s = 0.4$	12	,,	2 s = 0.42
,, $N$ $s =$	1.85	,,	$10 \ s = 0.4$	12	,,	1 s = 0.42
O s =	1.76					
", $O_1$ $s =$	1.92					
$O_2$ $s=$	1.77					

The list for the zones  $A\!-\!O$  gives the factors with which the correction for the compensation of these zones in the Hayford-Bowie system must be multiplied for getting the correction for the compensation in the new system; that for the zones  $18\!-\!1$  gives the factors with which the combined correction for topography and compensation in the Hayford-Bowie system must be multiplied for getting the combined correction in the new system.

For zone O a factor is given for the complete zone and also for each of the subdivisions  $O_1$  and  $O_2$ . The first has been used for the stations up to No 195 and the last ones for the subsequent stations. The factors for  $O_1$  and  $O_2$  have been based on new figures regarding the Hayford-Bowie correction for these subdivisions, which have been received from Mr. Swick of the U. S. Coast and Geodetic Survey.

By means of the above factors, the computation of the corrections for the regional method was an easy matter. The total results for each station are given in the two columns of the list of this chapter following on those of the Heiskanen corrections. The first of these columns gives the sum of the compensation-corrections for all the zones A-O and the second the sum of the combined corrections for topography and compensation for all the zones 18-1.

For the Bouguer reduction, as it has been applied here in this publication, no new computations were needed. The gravity results have been corrected for the effect of the topography of the zones A-O, that is to say up to a distance of 166.7 km, and, besides that, for the combined effect of the topography and the compensation for the remainder of the Earth's surface. This last part of the correction was applied in order to free the results as well as possible from the effects of distant areas; as isostasy has hitherto been found to be the best approximation to the actual gravity field, this object could best be attained in this way. From the three available sets of isostatic corrections for the zones 18-1, the set belonging to the regional method was chosen.

Taken together, the Bouguer reduction has thus consisted of the correction for the topography of the zones A-O, which is given in the first column of corrections in the list of this chapter, and of the combined correction for the topography and the compensation of the zones 18-1 which is found in the last column of corrections in this list.

The resulting anomalies according to these different systems of reduction are given in the last compartment of the list. The first column repeats the value of the mean error of the gravity determination as it has been published in the first volume of this publication. The second gives the free-air anomaly, found by comparing the value of gravity at sea-level with the formula for normal gravity; this anomaly has likewise been given in the first volume. The third column gives the Bouguer anomaly, the fourth the Hayford-Bowie isostatic anomaly, the fifth the Heiskanen isostatic anomaly and the last the regional isostatic anomaly.

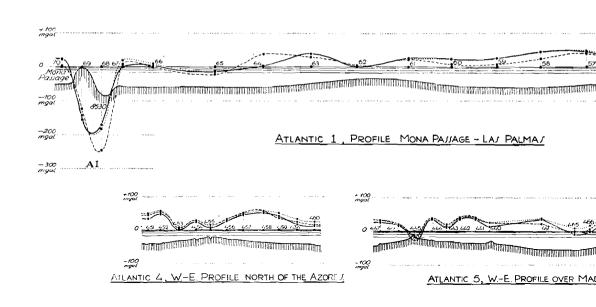
A few words may be said with regard to the first compartment of the list of this chapter, which gives the positions and the depths of the stations. The first column of this compartment gives the number of the station corresponding to the number in the closing list of the first volume and in the list of the previous chapter. The second and third columns give the latitudes and their mean errors in nautical miles of 1853 meters; the fourth and fifth the longitudes with their mean errors in nautical miles. The sixth column gives the depths in meters of the sea at the station, save for the harbour-stations, for which the name of the port is given.

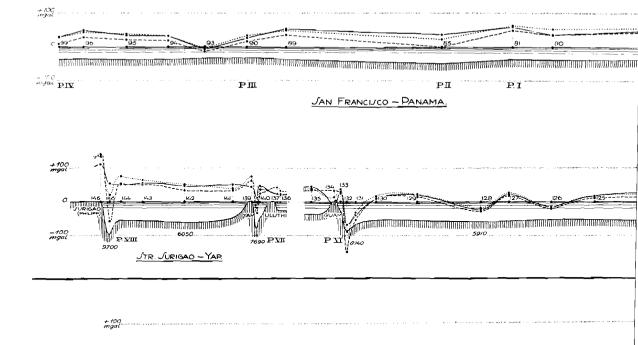
For the stations 1—32 the sea-depths have been derived from the charts. For all the other stations they have been determined by means of echo-soundings, save for the stations over depths of less than two hundred meters, where they have also been derived from the charts. The depths of the stations up to No 195 and those of the Nos 426—486 have been computed with the tables for the velocity of sound in sea-water of the Hydrographic Department of the British Admiralty. Those for the stations 196—425 in the Netherlands East Indies were computed with the following table

Depth	Veloc.	Depth	Veloc.	Depth	Veloc.
meters	m/sec	meters	m/sec	meters	m/sec
200	1530	2200	1493	4200	1505
400	1511	2400	1494	4400	1507
600	1503	2600	1495	4600	1508
800	1498	2800	1496	4800	1510
1000	1495	3000	1497	5000	1512
1200	1495	3200	1498	5200	1514
1400	1492	3400	1500	5400	1516
1600	1492	3600	1501	5600	1518
1800	1492	3800	1502	5800	1520
2000	1492	4000	1504	6000	1522

The accuracy of the depths for the numbers 33—42 is not more than 100—150 meters because of the primitive way in which the echo-intervals were measured for these stations. The accuracy of the stations 43—195 may be normally estimated at about 40 meters and that of all the subsequent stations at about 25 meters. For details about the way in which the soundings have been made, the writer may refer to the first volume of this publication. The depths in the list are given in meters.

## PLATE I.





INDIAN OCEAN

Hayford-Bowie Isostatic Anomalies.

Heiskanen Isostatic Anomalies.

Regional Isostatic Anomalies.

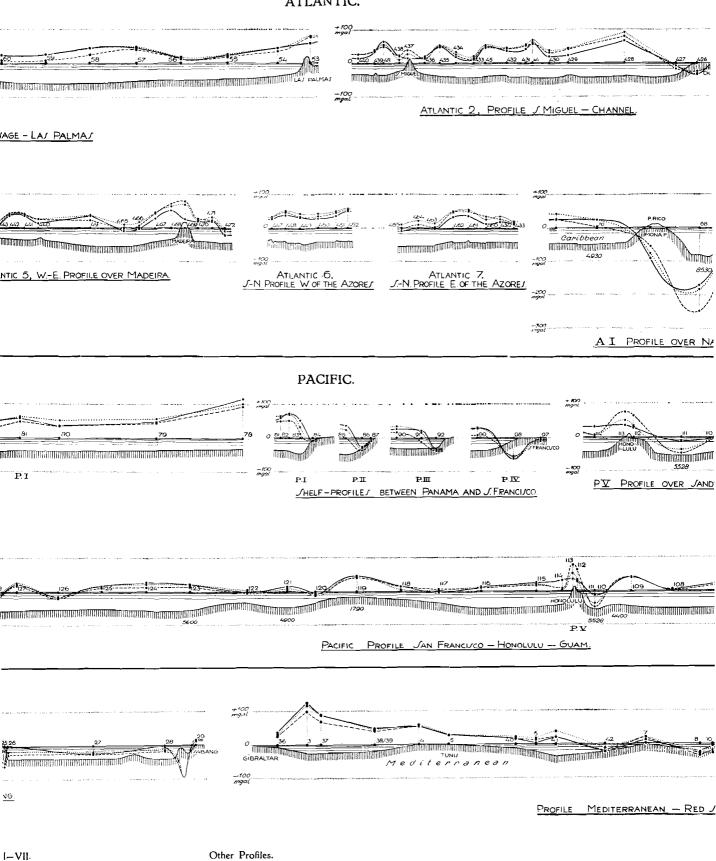
Profiles A I—II and P I—VII. Horizontal Scale 1:10.000.000 Vertical Scale 1:1.000.000

PROFILE JOKOTRA-JABANG

100 200 300 400 soo kr

# Gravity Profiles.

## ATLANTIC.



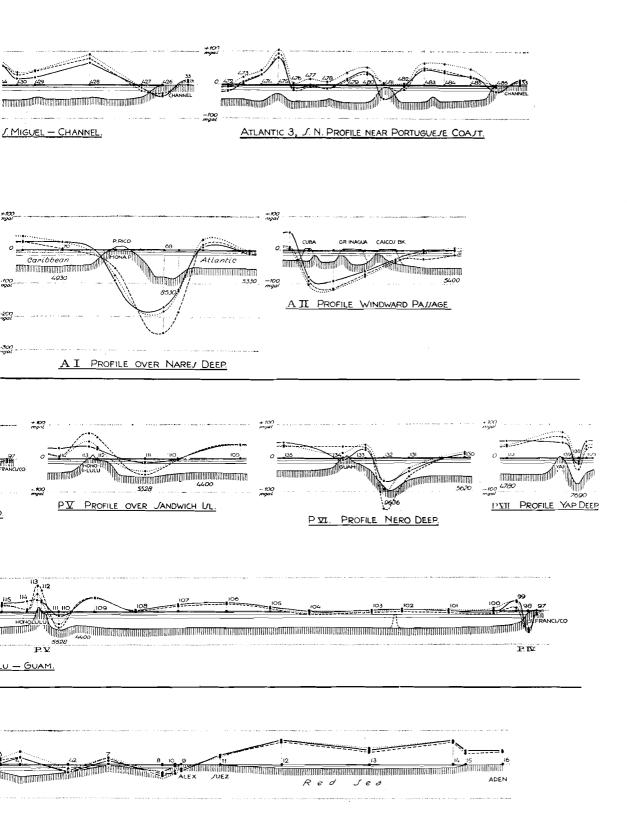
Vertical Scale

.000.000

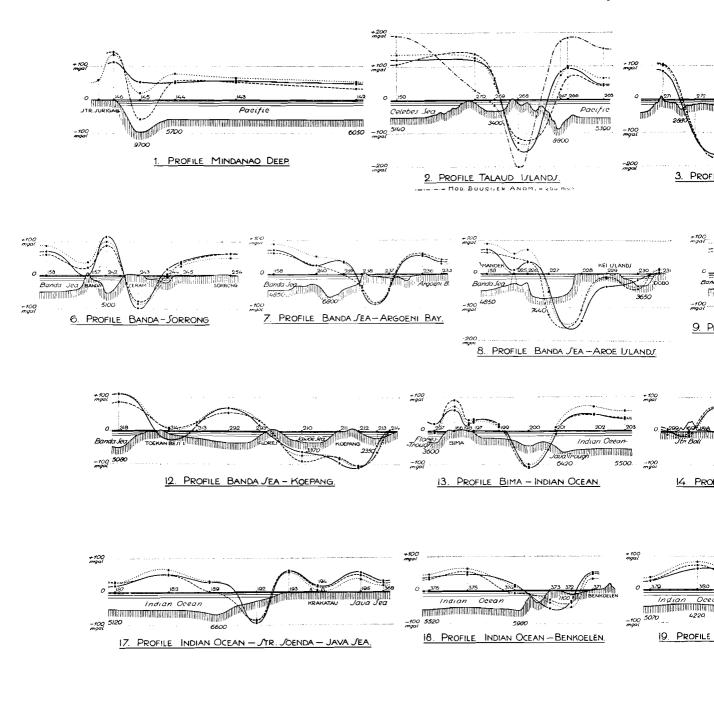
.000.000

Horizontal Scale 1:30.000.000

1: 1.000.000



PROFILE MEDITERRANEAN - RED JEA

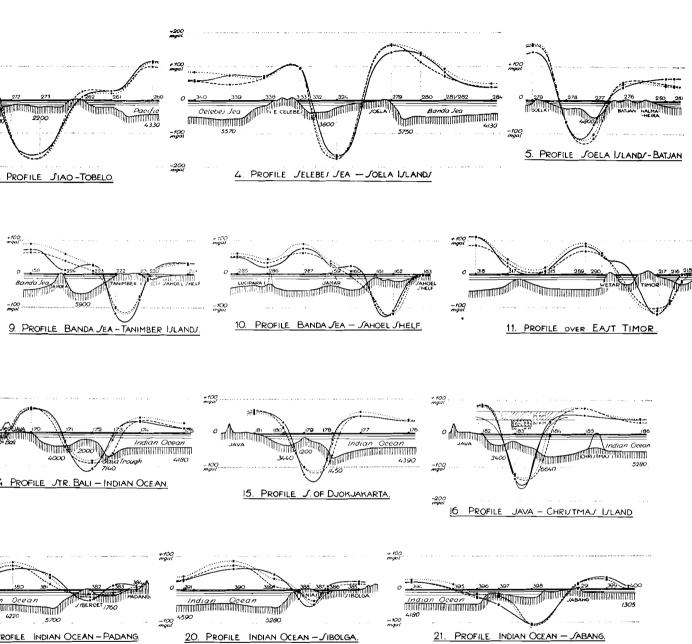


Hayford-Bowie Isostatic Anomalies.

Heiskanen Isostatic Anomalies. Regional Isostatic Anomalies. Horizontal Scale 1:10.000.000

Vertical Scale 1: 1.000.000

## in the East Indies.



#### § 2. Table of Free-air, Modified Bouquer and Isostatic Anomalies for all the Stations.

- 1. The number of the station of the last list of the 1st Volume and of the list of Chapter II.
- 2. The Latitude of the station,
- 3. Estimate of the Mean Error of the Latitude in nautical miles,
- 4. The Longitude of the station,
- 5. Estimate of the Mean Error of the Longitude in nautical miles,
- 6. The Depth of the sea in meters.
- 7. The Correction for the Topography of Zones A-O in 0.1 milligal,
- 8. The Hayford-Bowie Correction for the Compensation of Zones A-O in 0.1 milligal,
- 9. The Hayford-Bowie Correction for the Topography and Compensation of Zones 18-1 in 0.1 milligal,
- 10. The Heiskanen Correction for the Compensation of Zones A-O in 0.1 milligal,
- 11. The Heiskanen Correction for the Topography and Compensation of Zones 18-1 in 0.1 milligal,
- 12. The Regional Correction for the Compensation of Zones A-O in 0.1 milligal,
- 13. The Regional Correction for the Topography and Compensation of Zones 18-1 in 0.1 milligal,
- 14. The Mean Error of the Gravity Determination in milligal,
- 15. The Free-air Anomaly in milligal,
- 16. The Modified Bouguer Anomaly in milligal,
- 17. The Hayford-Bowie Isostatic Anomaly in milligal,
- 18. The Heiskanen Isostatic Anomaly in milligal,
- The Regional Isostatic Anomaly in milligal.
   All the anomalies are computed with regard to the formula of Cassinis for normal gravity.

Table of Free-air, Modified Bouguer and Isostatic Anomalies for all the Stations.

		es		es			(	Correctio	ns in 0.1	milligal	_		<u> </u>		Anoma	lies in r	nilligal	
No.	Latitude $\varphi$	$\varphi$ miles	Longitude λ	, miles	Depth meters	Topog	Hayford		Heisk		Regi		mg	Free air	Mod.	Hayf.	Heisk.	Region
		E		ä		A—O	comp. A—O	(t+c) 18—1	comp. A—O	(t+c) 18—1	A—O	(t+c) 18—1	Ļ	air	Boug.	isost.	isost.	isost.
1 2 3 4 5	36 55 N 36 52 ,, 36 17 ,, 37 01 ,; 36 47.6 ,,	2 2 2 2 0.0	7 20 W 7 42 ,, 1 05 ,, 7 55 E 10 11.4 ,,	2 2 2 2 0.0	110 540 2500 100 Tunis	84 409 1708 91 18	+ 83 + 180 + 834 + 202 — 55	+ 173 + 208 - 47 + 83 + 95	+ 92 + 184 + 989 + 243 — 67	+ 127 + 153 - 38 + 63 + 71	+ 98 + 211 + 754 + 271 - 53	+ 93 + 122 - 38 + 52 + 58	4 6 5	+ 29 + 6 + 24 + 78 + 28	+ 35 + 199 + 82	+ 12 + 8 + 116 + 59 + 26	+ 15 + 13 + 100 + 56 + 29	+ 123 + 55
6 7 8 9 10	34 58 ,, 32 06 ,, 31 58 ,, 31 09 ,, 31 32 ,,	2 2 2 0.2 2	16 47 ,, 24 32 ,, 28 52 ,, 29 52.4 ,, 29 44 ,,	2 2 0.2 2	2200 115 2020 Alexandria 620	— 1443 — 89 — 1442 — 14 — 411	+ 1024 + 217 + 900 + 122 + 325	+ 226 + 117 + 128 + 81 + 105	+ 1153 + 248 + 1043 + 139 + 357	+ 172 + 90 + 100 + 69 + 83	$\begin{array}{r} + \ 1229 \\ + \ 334 \\ + \ 973 \\ + \ 202 \\ + \ 421 \end{array}$	+ 175 + 83 + 99 + 61 + 83	4 5 2	$ \begin{array}{c cccc}  & - & 1 \\  & + & 44 \\  & - & 64 \\  & + & 6 \\  & - & 18 \end{array} $	+ 45 + 70 + 1	+ 18 + 19 - 23 - 13 - 20	+ 11 + 19 - 34 - 13 - 21	+ 3 + 11 27 19 27
11 12 13 14 15	29 56.0 ,; 26 12 ,, 20 42 ,, 15 11 ,, 14 24 ,,	0.2 2 2 2 2	32 33.3 ,, 35 02 ,, 38 28 ,, 41 58 ,, 42 30 ,,	0.2 2 2 2 2	Suez 1080 1260 830 80	— 9 — 691 — 866 — 550 — 64	- 173 + 304 + 452 + 99 - 45	- 68 - 145 - 142 - 192 - 186	- 212 + 356 + 536 + 98 - 39	54 122 107 148 141	- 255 + 267 + 444 + 30 - 131	42 85 78 121 118	5 4 5	$ \begin{array}{c cccc}  & - & 1 \\  & + & 20 \\  & - & 8 \\  & + & 5 \\  & + & 9 \end{array} $	+ 86 + 72	+ 24 + 73 + 48 + 69 + 39	+ 27 + 66 + 36 + 65 + 33	+ 29 + 71 + 42 + 69 + 40
16 17 18 19 20	12 47.6 ,, 11 54 ,, 10 02 ,, 7 57 ,, 7 53 ,,	0.0 2 2 2 2	44 58.8 ,, 53 04 ,, 55 25 ,, 61 54 ,, 65 58 ,,	0.0 2 2 2 2 2	Aden 80 4210 4390 4390	7 95 2817 3001 3006	- 53 + 433 + 1931 + 2069 + 2089	- 117 + 464 + 721 + 806 + 814	50 + 466 + 2223 + 2414 + 2434	- 89 + 329 + 483 + 529 + 538	- 101 + 709 + 2244 + 2395 + 2431	70 + 307 + 477 + 507 + 517	6 7 6 7 4	+ 21 + 19 - 19 - 9 - 33	$-2 \\ +215 \\ +240$	+ 39 - 61 - 3 + 4 - 23		_ 27
21 22 23 24 25	7 56 ,, 8 06 ,, 7 20 ,, 6 56.9 ,, 5 50 ,,	2 2 2 0.0 2	68 46 ,, 72 48 ,, 77 28 ,, 79 51.0 ,, 80 12 ,,	2 2 2 0.0 2	4390 1870 160 Colombo 65	— 2992 — 1238 — 356 — 12 — 218	+ 2081 + 971 + 597 + 157 + 833	+ 742 + 527 + 438 + 481 + 585	+ 2425 + 1102 + 431 + 173 + 1002	+ 497 + 370 + 306 + 330 + 401	+ 2404 + 1186 + 664 + 263 + 1163	+ 481 + 326 + 249 + 274 + 359	5 5 1 3	- 42 - 34 - 28 + 23 + 68	+ 57 - 17 - 3	- 25 - 60 - 96 - 40 - 52	— 35 — 57 — 66 — 26 — 50	- 61 - 84 - 30
26 27 28 29 30	5 32 ,, 5 44 ,, 6 02 ,, 5 53.2 ,, 6 01 ,,	2 2 2 0.0 2	80 12 ,, 87 07 92 50 ,, 95 18.7 ,, 96 55 .,,	2 2 2 0.0 2	3920 4020 4100 Sabang 1420	2712 2730 2645 47 937	+ 1530 + 1912 + 1497 + 424 + 431	+ 589 + 733 + 511 + 305 + 183	+ 1795 + 2216 + 1713 + 512 + 498	+ 404 + 491 + 357 + 209 + 127	+ 1605 + 2228 + 1612 + 588 + 396	+ 360 + 466 + 318 + 172 + 87	5 7 3 7 2 2	— 78 — 27 — 77 + 83 — 5	$\begin{array}{c} + 199 \\ + 156 \\ + 71 \end{array}$	19 19 13 + 15 + 27	- 27 - 25 - 19 + 16 + 26	- 5 + 12
31 32 33 34 35	6 01 ,, 4 26 ,, 49 04 ,, 44 59 ,, 37 22.8 ,,	2 2 2 2 0.0	96 59 ,, 98 53 ,, 5 55 W 8 39 ,, 6 00 ,,	2 2 2 0.0	1140 54 109 4720 Sevilla	- 763 - 54 - 102 - 3186 + 10	+ 390 + 4 + 53 + 2036 — 135	+ 178 + 103 + 171 + 503 + 73	+ 451 + 7 + 57 + 2415 - 165	+ 125 + 62 + 120 + 351 + 52	+ 372 - 8 + 58 + 2275 - 207	+ 84 + 31 + 81 + 342 + 25	1 7 1 7 2 6	$\begin{array}{c c}  & 0 \\  & 1 \\  & + 19 \\  & - 12 \\  & + 14 \end{array}$	$\begin{array}{c} + & 1 \\ + & 21 \\ + & 272 \end{array}$	$ \begin{array}{ccccc} + & 20 \\ - & 6 \\ + & 7 \\ + & 53 \\ + & 19 \end{array} $	$\begin{array}{ c c c } + & 19 \\ - & 2 \\ + & 11 \\ + & 30 \\ + & 24 \end{array}$	+ 15
36 37 38 39 40	36 10 ,, 36 52 ,, 37 08 ,, 37 05 ,, 36 20 ,,	2 2 2 2 2	3 25 ,, 0 01 E 4 17 ,, 4 28 ,, 15 31 ,,	2 2 2 2 2	620 2540 2300 1780 1130	- 467 - 1732 - 1598 - 1236 - 838	+ 249 + 992 + 670 + 588 + 679	— 26 — 28 + 85 + 79 + 192	+ 299 + 1188 + 727 + 646 + 794	25 23 + 66 + 61 + 146	+ 194 + 1003 + 627 + 577 + 785	- 32 - 22 + 66 + 60 + 128	6 10 13	$\begin{vmatrix} + & 6 \\ + & 10 \\ - & 34 \\ - & 19 \\ + & 25 \end{vmatrix}$	$\begin{array}{c} + 185 \\ + 119 \\ + 99 \end{array}$	+ 30 + 87 + 50 + 38 + 22	+ 25 + 67 + 46 + 34 + 15	+ 56 + 41
41 42 43 44 45	35 13 ,, 33 56 ,, 44 18 ,, 43 11 ,, 41 22 ,,	2 2 6 2 8	18 31 " 22 12 " 15 27 W 18 44 " 21 39 ",	2 2 6 2 2	3630 2180 5200 4570 4040	2463 1509 3329 3101 2771	$\begin{array}{r} +\ 1651 \\ +\ 993 \\ +\ 2158 \\ +\ 2160 \\ +\ 1956 \end{array}$	+ 290 + 204 + 803 + 769 + 749	$egin{array}{c} +\ 1694 \\ +\ 1125 \\ +\ 2512 \\ +\ 2532 \\ +\ 2271 \end{array}$	+ 213 + 146 + 528 + 509 + 499	+ 1890 + 1157 + 2444 + 2504 + 2264	$egin{pmatrix} + & 227 \\ + & 147 \\ + & 526 \\ + & 497 \\ + & 477 \end{bmatrix}$	7 6 5 4 7 4	16 45 17 + 50 + 45	$\begin{array}{c} + & 91 \\ + & 263 \\ + & 310 \end{array}$	+ 36 - 14 + 20 + 67 + 52	$\begin{array}{c cccc} + & 20 \\ - & 21 \\ + & 12 \\ + & 56 \\ + & 45 \end{array}$	
46 47 48 49 50	39 48 ,, 38 31.8 ,, 36 23 ,, 33 42 ,, 30 48 ,,	3 0.0 2 2 2	24 57 ,, 28 37.4 ,, 26 43 ,, 24 19 ,, 22 30 ,,	3 0.0 3 5 2	3580 Horta 3610 5480 5170	2406 27 2470 3579 3548	+ 1559 + 510 + 1579 + 2387 + 2499	+ 639 + 560 + 637 + 846 + 908	+ 1856 + 611 + 1853 + 2827 + 2939	+ 434 + 380 + 429 + 554 + 587	+ 1769 + 760 + 1747 + 2710 + 2909	+ 389 + 323 + 379 + 539 + 585	3 4 4	+ 50 + 111 + 30 + 3 + 2	$^{+}$ 81 $^{+}$ 239 $^{+}$ 307	+ 71 + 7 + 55 + 38 + 16	+ 62 + 15 + 49 + 23 + 4	+ 5 + 64 + 36
51 52 53 54 55	29 20 ,, 28 40 ,, 28 09.3 ,, 27 13 ,, 26 33 ,,	6 2 0.0 2 2	19 15 ,, 15 53 ,, 15 25.2 ,, 17 48 ,, 21 37 ,,	2 2 0.0 3 2	4610 3630 I. Palmas 3730 4780	- 3073 - 2283 - 132 - 2478 - 3232	+ 2098 + 1357 + 822 + 1635 + 2241	+ 772 + 531 + 452 + 607 + 837	$+\ 2459 \\ +\ 1541 \\ +\ 971 \\ +\ 1904 \\ +\ 2632$	+ 512 + 369 + 319 + 413 + 543	+ 2414 + 1490 + 1193 + 1846 + 2590		1 2	14 28 + 194 + 19 + 11	$+ 167 \\ + 179 \\ + 228$	+ 6 + 12 + 80 + 43 + 26	+ 35	+ 18 + 60 + 44
56 57 58 59 60	25 44 ,, 25 07 ,, 25 00 ., 24 34 ., 24 03 ,,	4 4 3 2 2	25 19 ,, 28 50 ,, 32 30 ,, 35 57 ,, 39 34 ,,	5 2 4 5 4	4990 5310 5920 5950 5490	3384 3601 4253 4089 3733	+ 2371 + 2495 + 2790 + 2749 + 2519	+ 952 + 978 + 1022 + 1015 + 951	+ 2776 + 2937 + 3357 + 3321 + 3012	+ 612 + 624 + 647 + 644 + 612	+ 2762 + 2889 + 3159 + 3142 + 2864		5 0 4 0 4	+ 12 + 36 - 1 - 5 - 4	$\begin{array}{c} + \ 334 \\ + \ 359 \\ \hline + \ 340 \end{array}$	+ 18 + 49 + 43 + 27 + 22	+ 40 + 24 + 7 + 7	+ 46 + 43 + 26 + 23
61 62 63 64 65	23 03 ,, 22 45 ,,	2 2 2 2 2	43 00 ,, 47 05 ,, 50 45 ,, 54 34 ,, 58 24 ,,	3 3 2 3	3970 3550 4870 5920 5880	2724 2503 3550 4001 3990	+ 1907 + 1869 + 2368 + 2715 + 2750	+ 864 + 863 + 966 + 1062 + 1099	+ 2208 + 2151 + 2783 + 2783 + 3261	+ 562 + 563 + 619 + 669 + 688	+ 3124	+ 530 + 602 + 673	4 2 4 1 4	+ 27 + 26 + 15 19 27	$\begin{array}{ccc} & + & 223 \\ & + & 310 \\ & + & 314 \end{array}$	+ 22 + 3 + 37 + 3 — 13	+ 30 + 36	$\begin{array}{c c}  & 0 \\  + & 39 \\  + & 2 \\  - & 15 \end{array}$
66 67 68 69 70	20 44 ,, 19 32 ,, 18 24 ,,	2 4 3 1 2	63 22 ,, 65 37 ,, 66 46 ,, 67 42 ,,	2 7 5 1 2	5690 5510 8040 290 49 <b>3</b> 0	— 3866 — 3763 — 5444 — 277 — 3309	+ 2699 + 2758 + 3140 + 790 + 2132	+ 1056 + 933 + 753 + 768 + 680	+ 3185 + 3203 + 4035 + 855 + 2551	+ 667 + 598 + 502 + 512 + 463	+ 3283 + 3308 + 1201	+ 60' + 46' + 48'	4 4	— 338	+ 160 - 36	183	+ 8 247 124	- 1 - 171 - 156

		les		les		Corrections in 0.1 milligal									Anoma	lies in n	nilligal	
No.	Latitude T	q miles	Longitude 2	-	Depth meters	Topog							mg	Free	Mod.	Hayf.	Heisk.	Region
_	,	E I		m,		A,O	A—O	(t+c) 18—1	comp. A—O	(t±c) 18—1		(t+c) 18—1	<u> </u>	air	Boug.	isost.	isost.	isost.
71 72 73 74 75	0 , 12 06.4 N 12 00 ,, 12 55 ,, 10 22 ,, 9 51 ,,	0.0 2 2 3 5	68 56.1 W 69 12 ,, 71 54 ,, 77 13 ,, 78 01 ,,	0.0 2 4 2 3	Curação 1130 1570 3320 1480	— 27 — 741 — 1109 — 2229 — 953	- · 444  : 447  - 866  - · 1418  - 735	+ 384 355 -: 434 297 305	-  618 -+ 487 -: 980 -+ 1646 -+ 912	+ 271 + 253 - 308 + 216 + 222	+ 640 + 511 + 1044 + 1570 + 852	+ 237 + 212 + 275 + 188 + 191	3 4 4 4 4	+ 160 12 66 39 22	139 41 17 + 165 + 54	- 80 - 18 - 85 + 12 - 31	+ 74 - 12 - 84 - 2 - 40	+ 75 - 10 - 87 + 8 - 31
76 77 78 79 80	9 22.4 ,, 8 57.5 ,, 7 01 ,, 10 21 ,, 13 35 ,,	0.0 0.0 2 2 2	79 53.3 ,, 79 33.9 ,, 82 37 ,, 88 30 ,, 95 27 ,,	0.0 0.0 2 5 2	Colon Panama 2990 3470 3870	12 9 2016 2378 2645	+ 163 12 + 1121 + 1681 + 1932	+ 294 + 334 + 342 + 484  - 521	+ 176 - 34 + 1315 + 1956 + 2270	+ 209 + 238 + 243 + 341 + 364	+ 285 + 19 + 1131 + 1957 + 2271	+ 175 + 201 + 199 + 315 + 346	3 3 4 4 4	+ 67 + 73 + 47 + 37 + 33	+ 51 + 54 + 229 + 243 + 263	$^{+}$ 23 $_{+}$ 42 $_{+}$ 102 $_{+}$ 58 $_{+}$ 52	+ 30 + 53 + 93 + 45 + 34	+ 22 + 52 + 116 + 48 + 36
81 82 83 84 85	15 03 ,, 15 17 ,, 15 35 ,, 15 55 ,. 17 35 ,,	5 2 2 5 7	98 20 ,, 98 23 ,, 98 20 ,, 98 16 ,, 103 26 ,,	5 2 2 3 2	3660 3970 4730 890 5030	— 2481 — 2670 — 3015 — 580 — 3178	-1 1653 -1 1626 -1 1458 -1 553 -1 1654	+ 440 + 371 + 316 + 273 + 338	- - 1936 - - 1917 - - 1750 - - 656 - - 1976	+ 310 + 266 -  227 + 195 + 242	+ 1877 + 1743 + 1398 + 714 + 1647	+ 276 + 226 + 184 + 151 + 209	4 4 4 4 4	+ 25 + 1 - 92 + 20 - 96	+ 245 + 245 + 191 + 63 + 201	+ 64 + 68 + 32 - 5 + 23	+ 49 + 50 + 12 7 0	+ 58 + 71 + 51 - 8 + 36
86 87 88 89 90	18 01 ,, 18 15 ,, 23 06.0 ,, 24 24 ,, 26 32 ,,	7 7 0.0 2 2	103 25 ,, 103 26 ,, 106 24.8 ,, 113 23 ,, 115 40 ,,	2 2 0.0 7 2	3050 710 Mazatlan 3610 3140	— 1855 — 524 — 31 — 2419 — 2364	+ 1015 + 539 54 + 1489 + 1683	+ 263 + 233 + 31 + 455 + 472	+ 1158 + 679 - 60 + 1751 + 1988	+ 189 + 165 + 43 + 321 + 333	$\begin{array}{rrr} + & 1091 \\ + & 695 \\ - & 90 \\ + & 1620 \\ + & 1940 \end{array}$	+ 147 + 126 - 1   + 281   298	4 4 3 4 4	- 88 + 21 + 25 0 + 12	+ 83 + 61 + 28 + 214 + 219	- 30 - 4 + 30 + 48 + 33	- 37 - 11 + 30 + 35 + 16	- 26 - 9 + 37 + 52 + 25
91 92 93 94 95	27 02 ., 27 20 29 13 31 01 33 12 .,	2 2 6 2 3	115 21 ,, 115 10 ,, 117 06 ,, 119 19 ,, 121 30 ,,	2 2 2 2 2	3340 3080 3320 3760 4010	— 2352 — 1782 — 2173 — 2465 — 2702	+ 1440 + 1011  - 1384 + 1544 + 1769	409 379 388 + 475 + 474	+ 1829 - 1142 + 1593 + 1806 - 2086	+ 291 + 271 + 278 + 334 + 336	+ 1546 + 1105 + 1565 - 1698 + 1977	+ 256 + 232 + 238 + 306 + 305	4 4 4 4	- 35 - 76 - 44 - 14 - 7	+ 175 + 79 + 150 + 202 + 233	+ 15 - 37 - 4 + 31 + 39	- 12 - 39 - 14 + 18 + 21	+ 20 - 32 - 7 + 32 + 35
96 97 98 99 100	35 50 ,, 37 48.5 ,, 37 29 ,, 37 06 ,, 36 22 ,,	2 0.0 5 3 2	122 43 122 25.9 ,. 123 09 ,, 123 54 125 22 ,,	2 0.0 6 2 4	3490 S.Francisco 680 3760 4520	2349 12 387 2511 3105	+ 19 + 19 + 466 +-1536 + 2129	+ 401 + 203 + 321 + 428 + 681	+ 1690 + 24 + 518 + 1846 + 2494	+ 285 + 145 + 231 + 305 + 464	+ 1530 + 60 + 649 - 1674 + 2456	+ 247 + 112 + 195 - 271 + 452	4 3 4 4 4	- 9 + 11 - 17 - 28 - 23	+ 201 + 1 + 2 + 196 + 242	+ 43 - 10 - 57 + 27 + 7	28 5 53 8 8	+ 48 - 5 - 63 + 29 - 3
101 102 103 104 105	34 46 ,, 33 15 ,, 32 12 ,, 30 15 ,, 28 57 ,,	2 2 2 2 2 2	128 34 ,, 131 52 ,, 134 01 ,, 138 25 ,, 141 14 ,,	7 2 2 5 2	4920 5120 4930 4820 4970	3335 3310 3198 3219 3344	+ 2312 + 2238 + 2224 + 2219 + 2334	+ 961 + 958 + 1014 + 1018	$   \begin{array}{r}     + 2712 \\     - 2631 \\     + 2599 \\     + 2610 \\     + 2741   \end{array} $	+ 581 + 621 + 618 + 645 + 648	+ 2672 - 2579 - 2556 - 2560 + 2707	+ 568 + 600 + 599 + 623 + 623	4 4 4 4 4	- 10 - 7 - 3 - 5 + 12	+ 267 + 264 + 257 + 255 + 284	3 + 4 1 6 + 11	- 6 - 1 - 5 - 9 + 8	+ 6 + 1 - 1 + 13
106 107 108 109 110	27 27 ,, 25 45 ,, 24 19 ,, 22 57 ,, 22 13 ,,	2 2 2 2 2	144 21 ,, 147 43 ,, 150 48 ,, 153 40 ,, 155 24 ,,	2 2 3 2 2	4900 5210 5270 4590 4510	3328 3601 3605 3228 3089	+ 2306 + 2504 + 2548 + 2275 + 2222	1050 +- 1082 +- 1115 1060 960	+ 2699 + 2945 + 2983 + 2650 + 2599	+ 663 + 680 + 701 - 669 + 612	+ 2674 + 2904 + 2982 + 2662 + 2605	+ 645 + 671 + 693 + 653 + 572	4 4 4 4	+ 25 + 17 + 11 + 49 + 7	+ 293 + 310 + 302 + 307 + 259	+ 22 + 19 + 5 + 38 - 2	+ 22 + 15 + 3 + 40 - 5	+ 26 + 20 + 4 + 40 2
111 112 113 114 115	21 45 ,, 21 09.0 ,, 21 18.4 ,, 20 48 ,, 20 29 ,,	2 1 0.0 2 2	156 13 ,, 157 28.0 ,, 157 52.0 ,, 158 36 ,, 160 30 ,,	2 1 0.0 2 4	5430 510 Honolulu 4290 4590	— 3672 — 300 — 43 — 2880 — 3104	+ 2157 + 721 + 765 1765 2134	+ 939 + 938 + 909 + 910 + 937	+ 2600 + 761 + 843 + 2100 + 2502	+ 597 + 598 + 582 + 573 + 602	+ 2298 + 1159 + 1287 + 1903 + 2462	+ 547 + 558 + 541 + 533 + 565	4 3 4 4	- 96 + 169 + 213 - 14 + 17	+ 216 143 163 221 271	- 38 + 33 + 50 + 6 + 20	- 48 + 63 + 75 + 7 + 17	- 13 + 27 + 35 + 30 + 25
116 117 118 119 120	19 58 ,, 19 31 ,, 19 07 ,, 18 37 ,, 18 06 ,,	2 2 2 3 2	164 56 ,, 168 27 ,, 171 35 ,, 175 00 ,, 178 14 ,,	6 2 3 4 2	4960 3520 2640 1790 3830	3341 2484 1897 2456 2613	+ 2352 + 1957 + 1595 + 1964 + 1856	+ 1003 + 963 + 920 + 925 + 929	$\begin{array}{c} +\ 2747 \\ -\ 2253 \\ +\ 1818 \\ +\ 2333 \\ +\ 2143 \end{array}$	+ 642 + 619 + 594 + 598 + 599	+ 2737 + 2372 + 1860 + 2316 + 2175	+ 621 + 598 + 557 + 564 + 563	4 4 4 4	+ 13 + 45 + 67 + 88 + 5	+ 285 + 234 + 201 + 277 + 210	+ 12 + 1 + 5 + 45 — 12	+ 8 + 6 + 15 + 40 - 8	+ 11 + 15 + 46 - 7
121 122 123 124 125	17 47 ,, 17 02 ,, 16 12 ,, 15 32 ,, 15 07 ,,	3 2 2 2 2 2	179 33 E 176 24 ,, 171 53 ,, 168 27 ,, 164 56 ,,	3 2 3 2 2	4900 3190 5600 5600 5330	— 3306 — 2700 — 3599 — 3715 — 3611	÷ 2230 ÷ 2231 + 2356 + 2460 + 2528	+ 931 + 963 + 960 + 1020 + 1046	+ 2620 + 2664 + 2763 + 2913 + 2976	+ 600 + 621 + 614 648 + 666	+ 2534 2663 + 2696 + 2785 + 2939	+ 571 + 596 + 593 + 637 + 655	4 4 4 4	- 6 + 53 - 8 - 2 + 13	+ 268 + 263 + 293 + 306 + 309	$\begin{array}{cccc} + & 8 \\ + & 4 \\ + & 20 \\ + & 22 \\ + & 17 \end{array}$	$\begin{array}{c cccc} + & 3 \\ - & 5 \\ + & 14 \\ + & 13 \\ + & 10 \\ \end{array}$	+ 14 - 3 + 23 + 27 + 15
126 127 128 129 130	13 38 ,,	2 2 2 2 2	155 56 ,, 150 58 ,,	4 2 2 3 2	5490 5870 5910 5770 5620	— 3744 — 4387 — 3998 — 3959 — 3826	+ 2609 + 2802 - 2806 + 2743 + 2663	+ 1083 + 1131 - 1134 + 1093 + 1074	+ 3072 + 3309 + 3320 + 3241 + 3128	+ 680 + 707 + 705 + 688 + 677	+ 3034 + 3265 + 3265 + 3187 + 3103	+ 675 + 714 + 716 + 697 + 700	4 4 4 4	- 20 - 20 - 25 + 11 + 7	+ 287 + 347 + 303 + 337 + 320	15 + 25 19 + 23 + 16	- 21 + 17 - 28 + 14 + 9	- 16 + 21 - 23 + 19 + 9
131 132 133 134 135	12 20 ,, 12 48 ,, 13 08 ,, 13 26.8 ,, 13 42 ,,	5 4 4 0.0 2	144 39.8 ,,	2 4 2 0.0 2	6660 8740 2850 Guam 3610	4746 5731 2886 117 2499	+ 3199 + 3195 + 2354 + 1099 + 1740	+ 998 + 1000 + 989 + 989 + 904	+ 3798 + 4131 + 2805 1268 + 2082	+ 638 + 639 + 633 + 633 ÷ 585	3658 + 3322 + 2852 + 1674 + 2010	+ 632 + 633 + 628 + 623 + 548	4 4 3 4	- 86 247 + 84 + 211 + 51	$^{+}$ 325 $^{+}$ 263 $^{+}$ 310 $^{+}$ 160 $^{+}$ 246	- 31 - 93 + 38 + 14 + 37	- 55 - 151 + 29 + 33 + 34	- 40 - 69 + 25 - 7 + 45
136 137 138 139 140	10 35 ,, 9 57 ,, 9 25 ,, 9 30.7 ,, 9 21 ,,	2 2 2 0.0 2	140 23 ,, 140 05 ,, 138 34 ,, 138 10.4 ,, 138 47 ,,	2 2 3 0.0 2	2600 2350 7690 Yap 4510	1779 1502 4349 291 3090	+ 1434 + 1207 + 2224 + 1570 + 1971	+ 883 + 861 + 819 + 836 + 820	+ 1646 + 1314 + 2664 + 1997 + 2354	+ 573 + 563 + 537 + 546 + 537	+ 1793 + 1558 + 2244 + 2213 + 2166	+ 542 + 528 + 499 + 511 + 496	4 4 3 4	$^{+\ 77}_{+\ 81}_{-\ 149}_{+\ 288}_{+\ 5}$	+ 201 + 178 + 236 + 266 + 264	+ 23 + 24 - 18 + 76 + 35	+ 33 + 43 - 34 + 63 + 25	+ 21 + 23 + 12 + 45 + 48

		es		es			C	orrection	ns in 0.1	milliga	1			1	Anoma	lies in r	nilligal	
No.	Latitude arphi	miles	Longitude 1	miles	Depth meters	Topog	Hayfor	d-Bowie	Heisk		Regi		mg	Free	Mod.	Hayf.	Heisk.	Region
	Ψ	m		E ,	meters	A—O	comp. A—O	(t+c) 18—1	comp. A—-O	(t+c) 18—1	comp. A—O	(t + c) 18—1		air	Boug.	isost.	isost.	isost.
141 142 143 144 145	9 30 N 9 52 ,, 10 12 ,, 10 19 ,, 10 17 ,,	6 2 2 2 2	136 36 E 132 46 ,, 129 22 ,, 127 39 ,, 126 41 ,,	6 2 2 2 3	4780 6050 5740 5730 8740	3140 4118 3929 3958 5954	$^{+\ 2001}_{+\ 2782}_{+\ 2723}_{+\ 2863}_{+\ 3051}$	+ 896 + 988 + 1018 + 819 + 709	+ 2359 + 3321 + 3219 + 3349 + 4079	+ 579 + 634 + 647 + 544 + 475	+ 2230 + 3192 + 3162 + 3397 + 2996	+ 551 + 625 + 665 + 523 + 443	4 4 4 4	+ 15 + 17 + 46 + 48 - 198	+ 274 + 366 + 372 + 391 + 353	+ 39 + 52 + 65 + 76 + 21	+ 35 + 33 + 52 + 54 - 58	+ 51 + 47 + 56 + 51 + 54
146 147 148 149 150	10 16 ,, 13 19 ,, 14 35.2 ,, 8 50 ,, 4 35 ,,	2 2 0.0 2 2	125 59 ,, 121 38 ,, 120 57.9 ,, 121 52 ,, 123 44 ,,	2 2 0.0 2 2	50 541 Manila 4870 5140	187 361 9 3308 3451	+ 926 + 62 30 + 1777 + 2366	+ 626 + 343 + 398 + 324 + 523	+ 1061 + 49 63 + 2185 + 2796	+ 427 + 232 + 276 + 228 + 372	+ 1399 + 10 - 20 + 1771 - 2709	+ 380 + 172 + 223 + 178 + 350	4 4 3 4 4	+ 270 + 20 14 29 + 80	+ 251 + 39 - 35 + 284 - 390	+ 134 + 16 50 + 92 136	+ 140 + 28 - 34 + 61 + 108	+ 111 + 33 - 33 + 107 + 119
151 152 153 154 155	. 0 29 S 1 45 ,, 2 35 ,, 3 23 ,, 3 41.3 ,,	2 2 2 2 0.0	125 59 ,, 126 57 ,, 127 12 ,, 127 27 ,, 128 10.4 ,,	2 2 2 2 0.0	2390 1390 5190 3550 Amboina	— 1609 — 1069 — 2910 — 1665 — 113	+ 1114 + 872 + 1247 + 773 + 736	+ 374 + 357 + 443 + 441 + 455	+ 1285 + 1009 + 1475 + 759 + 890	+ 265 + 253 + 316 + 312 + 322	$egin{array}{c} + \ 1287 \\ + \ 1051 \\ + \ 1086 \\ + \ 898 \\ + \ 1085 \\ \end{array}$	+ 215 + 203 + 281 + 284 + 295	4 4 4 4 2	$ \begin{array}{r} -216 \\ + 4 \\ - 7 \\ - 66 \\ + 114 \end{array} $	77 + 91 + 256 + 72 + 96	$\begin{array}{r} -204 \\ -12 \\ +115 \\ -21 \\ \div 6 \end{array}$	- 210 - 15 + 105 - 7 + 4	205 14 + 147 18 13
156 157 158 159 160	3 59 ,, 4 32.0 ,, 5 36 ,, 7 10 ,, 7 40 ,,	2 0.0 2 1 1	129 23 ,, 129 53.7 ,, 129 28 ,, 128 54 ,, 128 47 ,,	2 0.0 2 1 1	4520 Banda 4850 3430 4610	— 2922 — 203 — 3256 — 2036 — 2970	+ 1489 + 1314 + 2183 + 1390 + 1494	+ 446 + 417 + 455 + 393 + 367	$\begin{array}{r} +\ 1777 \\ +\ 1592 \\ +\ 2580 \\ +\ 1582 \\ -\ 1758 \end{array}$	+ 319 + 300 + 322 + 283 + 266	+ 1432 + 1860 + 2486 + 1666 + 1461	+ 293 + 275 + 332 + 269 + 247	4 2 4 4 4	$\begin{array}{r} - & 22 \\ + & 193 \\ \div & 27 \\ + & 14 \\ - & 102 \end{array}$	$\begin{array}{r} + 241 \\ + 186 \\ + 319 \\ + 191 \\ + 170 \\ \end{array}$	+ 77 + 40 + 89 + 39 + 9	+ 61 + 24 + 62 + 31 - 7	+ 98 0 + 71 + 24 + 24
161 162 163 164 165	8 13 ,, 8 48 ,, 9 36 ,, 7 52 ,, 7 45 ,,	1 1 1 1	128 33 ., 128 26 ., 128 07 ., 121 57 ., 119 58 ,,	1 1 1 1 1	1060 2120 340 2570 4990	711 1423 90 1728 3181	+ 738 + 762 + 279 + 902 + 1483	+ 341 + 294 + 223 + 359 + 265	+ 854 + 849 + 333 + 1012 + 1823	+ 246 + 212 + 162 + 261 + 188	992 796 400 892 1317	+ 221 + 183 + 129 - 232 + 142	4 4 4 4	$\begin{array}{rrr} - & 42 \\ - & 151 \\ + & 41 \\ + & 9 \\ - & 111 \end{array}$	+ 7 - 27 + 37 + 159 193	$\begin{array}{c c} - & 79 \\ - & 114 \\ 0 \\ + & 56 \\ + & 32 \end{array}$	- 81 - 115 + 1 - 55 + 6	- 92 107 3 69 61
166 167 168 169 170	8 27.1 ,, 7 53 ,, 7 12.1 ,, 8 05.5 ,, 8 51 ,,	0.1 1 0.0 0.2 1	118 42.7 ,, 114 54 ,, 112 44.6 ,, 114 25.5 ,, 114 38 ,,	0.1 1 0.0 0.2 4	Bima 910 Soerabaja 150 270	- 61 - 608 - 11 - 110 - 313	+ 184 + 169 - 64 + 11 - 593	343 + 318 + 256 - 340 + 416	+ 93 + 156 - 78 - 12 + 701	: 245 + 223 + 177 + 240 - 294	+ 431 + 121 - 104 + 108 + 795	+ 200 + 178 + 127 + 192 + 247	4 4 2 4	+ 119 + 28 - 7 + 7 + 141	- 105 + 71 - 5 - 1 + 148	+ 72 40 11 17 71	+ 91 + 51 - 2 - 5 + 73	+ 62 + 59 + 6 - 12 + 68
171 172 173 174 175	9 41 ,, 10 23 ,, 10 59 ,. 11 40 ., 12 47 ,,	3 2 2 3	114 15 ,, 113 55 ,, 113 40 ,, 113 15 ,, 112 46 ,,	2 2 2 2 3	3950 2680 6680 4280 4180	— 2623 — 1906 — 4340 — 2917 — 2813	$\begin{array}{r} +\ 1617 \\ +\ 1711 \\ +\ 2418 \\ +\ 2107 \\ +\ 1999 \end{array}$	+ 500 + 581 + 660 + 727 + 742	+ 1906 + 1966 + 3025 + 2453 + 2335	+ 351 + 403 + 449 + 489 - 552	+ 1751 + 2168 + 2509 2482 + 2342	+ 312 + 375 + 435 + 475 + 549		80 44 148 + 37 + 22	: 151 109 242 281 248	- 29 - 83 - 22 + 45 + 29	- 43 - 90 - 61 + 35 + 15	- 24 108 - 8 ! 33 + 14
176 177 178 179 180	12 24 11 05 ., 10 18 9 31 ., 9 00 .,	3 2 3 2	110 00 110 04 110 03 110 18 110 33	3 2 2 2 2	4390 5040 7080 1320 3020	— 2992 — 3426 — 4467 — 1076 — 2053	+ 2089 + 2392 = 2488 + 1338 + 1190	+ 872 + 745 - 675 + 566 + 513	+ 2433 + 2773 + 3041 + 1534 + 1372	+ 570 + 498 + 458 + 392 : 358	-!- 2430 -! 2781 2601 -! 1788 1251	+ 568 + 482 + 435 + 354 + 313	4 4 4 4	+ 35 + 33 - 163 - 16 - 17	+ 277 + 327 + 240 + 56 + 157	+ 38 + 62 - 33 - 99 + 18	+ 34 + 49 - 66 - 101 + 15	+ 34 + 49 - 20 - 123 + 32
181 182 183 184 185	8 14 ,, 7 35 ,, 8 26 ,, 9 21 ,, 10 13 ,,	2 2 2 2 3	110 32 ,, 106 55 ,. 106 36 ,. 106 21 ,. 105 55 ,,	2 2 2 2 2 2	130 230 2210 6610 4780	— 106 — 245 — 1690 — 4506 — 3151	+ 237 + 501 + 1533 + 2746 + 2340	+ 416 + 517 + 606 + 744 + 861	+ 266 + 597 + 1775 + 3385 + 2644	- 292  - 357  - 414  - 499  - 564	- - 384 - - 653 - - 1915 - - 2984 - - 2854	- - 236 - - 310 - - 377 - - 487 - - 568	4 4 4	+ 113 + 157 - 75 - 67 + 81	+ 100 + 151 + 56 + 335 + 339	+ 58 + 80 - 120 + 35 + 76		+ 62 + 85 - 135 + 37 + 54
186 187 188 189 190	11 42 10 38 9 00 7 46 7 04	2 3 4 2	105 24 ,, 102 29 ,, 102 47 ,, 103 09 ,, 102 29 ,,	2 3 4 2	5280 5120 5380 6260 4410	— 3612 — 3486 — 3738 — 4240 — 3137	+ 2480 + 2499 + 2625 + 2679 + 2118	+ 969 + 980 + 882 + 737 + 693	- - 2940 -  2832 3086 -  3250 -  2512	621 627 576 494 468	+ 2855 + 2936 + 3065 + 2961 + 2408	+ 631 + 630 + 581 + 479 + 417	4	+ 29 + 27 + 44 - 49 - 19	+ 327 + 313 + 360 + 327 + 250	+ 45 + 28 + 67 + 33 + 14	+ 34 + 30 + 52 + 1 - 3	- - 42 - - 19 - - 53 -  31 -  9
191 192 193 194 195	6 42 ,, 6 58 ,, 6 17 ,, 6 05.3 ,, 6 05.6 ,,	3 2 2 0.2 0.0	102 55 ,, 104 07 ,, 104 41 ., 105 37.0 ., 106 53.0 ,,	2 2 2 0.2 0.0	2410 2090 50 40 T. Priok	— 1757 — 1444 — 55 — 47 — 13	+ 1482 + 1236 + 375 + 55 66	+ 630 + 567 + 458 + 373 + 323	+ 1699 + 1406 - 458 + 52 - 81	+ 428 + 391 + 318 + 261 + 217	+ 1831 1534 + 517 89 108	+ 395 + 350 + 266 + 202 + 166	4 4 4	$\begin{array}{rrr} -&23\\ -&49\\ +&135\\ +&42\\ +&60\\ \end{array}$	+ 113 + 60 + 114 + 26 + 45	- 59 - 85 + 57 + 36		- 70 - 93 + 62 + 18 + 56
196 197 198	7 47 ,, 8 54 ,, 8 45 ,,	2 1 1	116 16 ,, 118 13 ,, 118 25 ,,	2 1 1	1443 500 Tjempi B. (Soembawa)	— 990 — 386 — 28	+ 400 + 410  - 276	+ 307 + 435 + 404	+ 449 + 457 + 313	-⊦ 214 + 300 -⊦ 280			3	+ 72 + 88	⊹ 86 84 66	+ 32 - - 26 -⊢ 23	÷ 37 ÷ 35 ÷ 32	+ 53 + 28 + 17
199 200	9 32 ,, 10 23 ,,	1 5	118 10 ,, 117 56 ,,	1 5	2298 4234	— 1598 — 2776	1017 1838	+ 498 + 525	+ 1163 + 2119	÷ 340 ÷ 353	+ 1137 + 2127	+ 330 + 330		- · 4 — 140	- 133   105	12 99	+ 14 110	+ 19 — 108
201 202 203 204 205	11 01 ,, 12 00 ,, 12 45 ,, 11 36.5 ,, 11 13 ,,	5 5 3 1 3	117 47 ,, 117 25 ,, 117 12 ,, 118 34.5 ,, 119 20 ,,	5 3 1 3	4600 5400 5500 4900 6370	3220 3742 3745 3451 3972	+ 2250 + 2597 + 2623 + 2435 + 2170	+ 603 + 741 + 793 + 595 + 534	+ 2650 + 3094 + 3091 - 2891 + 2595	+ 406 + 499 + 522 + 401 - 361	- 2863	-⊢ 543 -⊦ 399	5 4 5	$\begin{array}{c} - & 26 \\ + & 32 \\ + & 25 \\ + & 33 \\ - & 111 \end{array}$	+ 256 + 355 + 345 + 338 + 251	+ 11 + 72 + 58 + 75 + 16	- 10 + 47 + 33 + 49 - 9	- 10 + 50 + 34 + 51 + 22
206 207 208 209 210	10 20.7 ,, 10 22 ,, 9 29.5 ,, 8 54.5 ,,	0.1 2 0.5 0,5	120 25.6 ,, 121 05 ,, 121 21 ,, 121 36 ,,	0.1 2 0.5 0.5	280 1582 2512 Endeh (960) 3100	- 253 - 924 - 1704 - 681 - 2150	+ 437 + 597 + 890 + 635 + 1262	+ 469 + 436 + 404 + 363 + 341	+ 468 + 638 + 1037 - 703	324 303 289 258	- - 681	- · 218	3 3 4	+ 110 34 41 + 58	+ 106 - 32 + 105 + 104 + 68	+ 45 45 0 + 26	İ	+ 36
	,,	-	,,		2200	2100	, 1202	, 511	, 1000		7- 1309	· <del>-</del> 203	*	— 127	+ 68	72	— 90	63

		es		es		Corrections in 0.1 milligal Hayford-Bowie Heiskanen Regional									Anoma	lies in r	nilligal	
No.	Latitude	miles,	Longitude	miles	Depth	Topog	Hayfor	d-Bowie	Heisk	anen	Regi	onal	mg	Free	Mod.	Hayf.	Heisk.	Region.
	φ	m	λ	m	meters	A—O	comp. A.—O	(t+e) 18—1	comp. A—O	(t+c) 18—1	comp. AO	(t+c) 181	"	air	Boug.	isost.	isost.	isost.
211 212 213 214 215	11 10 ,,	0.2 1 3 5	0 / 123 32.0 E 123 48.2 , 124 10 , 124 21 , 126 43 ,	0.2 1 3 5	Koepang 205 2240 840 462	119 152 1423 545 295	+ 380 + 342 + 541 + 345 + 327	+ 293 + 304 + 268 + 252 + 213	+ 422 + 396 + 598 + 398 + 378	+ 209 + 219 + 193 + 178 + 152	+ 634 + 500 + 448 + 397 + 562	+ 169 + 181 + 156 + 137 + 112	3 4 4 4 3	29 58 126 + 2 + 35	- 34 - 61 + 1 + 43 + 53	- 84 107 65 3 + 11	80 104 63 1 + 11	97 111 44 + 3 3
216 217 218 219 220	8 54 ,, 9 19 ,,	3 2 2 2 2	126 37 ,, 126 40 ,, 127 09 ,, 131 04 ,, 131 00 ,,	3 2 2 2 2	1543 490 2970 230 1393	— 1106 — 360 — 1868 — 123 — 654	+ 648 + 434 + 866 + 135 + 356	+ 326 + 361 + 292 + 174 + 264	+ 726 + 470 + 996 + 151 + 390	+ 230 + 253 + 205 + 124 + 189	+ 693 + 670 + 797 + 179 + 390	+ 193 + 229 + 171 + 92 + 164	3 4 5 5 4	- 100 - 66 - 92 + 47 - 23	9 53 + 78 + 50 + 26	- 87 - 110 - 21 + 28 - 20	- 85 - 102 - 25 + 32 - 16	- 78 - 120 - 2 + 32 - 13
221 222 223 224 225	7 58.8 ,, 7 39.0 ,, 7 05 ,, 6 18.6 ,, 5 40 ,,	0.1 1 2 1 2	131 17.7 ,, 130 46.2 ,, 130 24 ,, 130 04.0 ,, 130 12 ,,	0.1 1 2 1 2	Saumlaki 480 4772 1544 2995	12 354 2934 1581 2209	+ 277 + 602 + 1638 + 1829 + 1939	+ 290 + 332 + 390 + 386 + 377	$egin{array}{cccc} + & 314 \\ + & 668 \\ + & 1910 \\ + & 2143 \\ + & 2171 \\ \end{array}$	+ 204 + 234 + 273 + 270 + 269	+ 444 + 884 + 1744 + 2419 + 2548	+ 187 + 218 + 266 + 267 + 261	3 3 3 3	- 15 - 43 - 67 + 122 + 71	- 33 - 29 + 200 + 253 + 266	71 101 + 24 + 59 + 60	66 98 + 8 + 39 + 48	- 77 - 118 + 26 + 12 + 11
226 227 228 229 230	5 36 ,, 5 39 ,, 5 37.8 ,,	3 3 1 0.1 3	132 42.9 ,,	3 3 1 0.1 3	2721 7330 525 Toeal 3650	— 2752 — 4940 — 376 — 16 — 2332	+ 2263 + 2678 + 806 + 455 + 996	+ 349 + 341 + 327 + 292 + 197	+ 2714 + 3465 + 900 + 495 + 1129	+ 248 + 244 + 234 + 205 + 139	+ 2756 + 2703 + 1235 + 785 + 900	+ 232 + 222 + 216 + 190 + 104	3 4 3 3 3	+ 57 - 245 - 33 + 58 - 152	+ 309 + 227 17 + 41 + 71	+ 71 - 53 - 109 - 15 - 38	+ 36 122 109 10 46	+ 33 43 141 38 19
231 232 233 234 235	5 45.3 ,, 4 42 ,, 3 45.0 ,, 3 26.3 ,, 3 13.8 ,,	0.1 2 0.1 0.1 0.1	134 12.2 ,, 133 38 ,, 133 39.5 ,, 133 36.2 ,, 133 38.5 ,,	0.1 2 0.1 0.1 0.1	Dobo 2055 10 15 15	36 1500 6 29 20	+ 333 + 906 + 63 — 86 — 136	+ 153 + 194 + 245 + 247 + 257	+ 405 + 1103 + 52 - 127 - 96	+ 107 + 134 + 171 + 170 + 177	+ 521 + 890 + 141 - 60 - 132	+ 75 + 90 + 123 + 124 + 129	3 3 3 3 3	+ 58 - 39 + 63 + 41 + 40	$\begin{array}{r} + & 54 \\ + & 102 \\ + & 51 \\ + & 31 \\ + & 29 \end{array}$	+ 13 + 1 + 33 + 28 + 30	+ 10 - 13 + 41 + 40 + 34	+ 2 + 13 + 37 + 37 + 42
236 237 238 239 240	4 07.2 ,, 4 31 ,, 4 45.1 ,, 4 52 ,, 4 58 ,,	0.2 2 0.2 2 4		0.2 2 0.2 2 4	340 1172 812 5080 3330	— 113 — 764 — 833 — 3543 — 2598	+ 318 + 610 + 1104 + 2056 + 2025	+ 246 + 322 + 346 + 351 + 365	$egin{array}{cccc} +&372 \ +&679 \ +&1278 \ +&2520 \ +&2414 \ \end{array}$	+ 172 + 232 + 248 + 250 + 258	+ 483 + 759 + 1480 + 2156 + 2431	+ 128 + 208 + 219 + 227 + 243	3 3 3 3	+ 103 - 30 + 28 - 80 + 32	+ 102 + 26 + 89 + 252 + 268	+ 58 - 47 - 34 + 34 + 53	+ 60 - 45 - 41 - 3 + 25	+ 53 - 50 - 59 + 36 + 24
241 242 243 244 245	4 20 ,, 4 13 ,, 3 29.5 ,, 2 33 ,, 2 17 ,,	3 1 0.5 2	130 51.5 ,, 130 54 ,,	3 1 0.5 2	2128 5100 50 2065 90	— 1653 — 3214 — 38 — 1199 — 86	+ 1382 + 1593 + 378 + 340 + 112	+ 493 + 400 + 352 + 344 + 342	+ 1615 + 1836 + 415 + 341 + 141	+ 339 + 279 + 245 + 241 + 236	+ 1678 + 1607 + 643 + 258 + 154	+ 319 + 250 + 210 + 186 + 177	3 4 3 4 4	+ 76 - 21 - 15 - 58 + 64	+ 209 + 275 - 32 + 43 + 55	+ 54 + 101 - 84 - 6 + 27	+ 46 + 89 - 77 + 4 + 35	+ 42 + 115 97 + 18 + 40
246 247 248 249 250	2 12.8 ,, 2 20 ,, 2 26 ., 1 23 ,, 0 40 ,,	0.1 1 2 2 2	130 21.6 ,, 129 28 ,, 128 09 ,, 128 23 ,, 128 43 ,,	0.1 1 2 2 2	10 1350 4200 900 955	— 23 882 2448 604 680	+ 138 + 414 + 1087 + 495 + 465	+ 350 + 377 + 406 + 366 + 386	+ 174 + 457 + 1265 + 545 + 549	+ 241 + 262 + 283 + 256 + 266	+ 192 + 387 + 965 + 644 + 516	+ 186 + 213 + 242 + 206 + 210	3 4 4 4	+ 80 - 2 - 162 + 48 + 71	+ 64 + 65 + 59 + 88 + 118	+ 34 + 7 - 66 + 22 + 54	+ 41 + 14 - 72 + 28 + 57	+ 44 + 26 - 38 + 23 + 66
251 252 253 254 255	0 18 ,, 0 38.5 ,, 0 56.5 ,, 0 53.5 ,, 0 26 ,,	3 1 1 0.0 1.5	128 48 ,, 129 34 ,, 130 14.5 ,, 131 14.2 ,, 131 42 ,,	3 1 1 0.0 1.5	1960 1340 820 Sorrong 2510	1320 840 560 31 1561	+ 583 + 408 + 213 + 56 + 568	+ 397 + 386 + 379 + 389 + 413	+ 668 + 453 + 221 + 57 + 585	+ 270 + 256 + 260 + 266 + 281	+ 501 + 429 + 199 + 102 + 502	+ 214 + 205 + 203 + 211 + 229	4 4 3 4	+ 8 + 12 + 67 + 93 - 36	+ 119 + 76 + 103 + 75 + 97	+ 42 + 17 + 64 + 52 + 22	+ 46 + 25 + 75 + 64 + 34	+ 68 + 33 + 83 + 65 + 47
256 257 258 259 260	0 19.5 ,, 0 20 N 1 03.2 ,, 1 27 ,, 2 03 ,,	0.2 1.5 0.2 1.5 5	132 38.5 ,, 132 39 ,, 131 16.5 ,, 130 46 ,, 129 55 ,,	0.2 1.5 0.2 1.5 5	545 4500 1297 4100 4330	— 519 — 3028 — 989 — 2574 — 2917	+ 546 + 1754 + 1298 + 1540 + 1778	+ 428 + 466 + 499 + 533 + 570	+ 639 + 2106 + 1523 + 1783 + 2103	+ 293 + 314 + 343 + 367 + 384	+ 813 + 1842 + 1710 + 1700 + 1971	+ 249 + 276 + 298 + 327 + 344	3 3 4 4	+ 119 + 52 + 115 + 59 + 56	+ 146 + 327 + 184 + 284 + 313	+ 73 + 133 + 34 + 109 + 113	+ 78 + 113 + 27 + 101 + 99	+ 65 + 143 + 13 + 114 + 116
261 262 263 264 265	1 52 ,, 1 43.7 ,, 2 49 ,, 3 23 ,, 4 42 ,,	2 0.0 2 1 1.5	128 48 128 00.7 ,. 128 34 ,. 129 09 129 23 ,.	2 0.0 2 1 6	2080 Tobelo 455 5172 5390	— 1456 — 20 — 636 — 3395 — 3717	+ 956 + 298 + 1152 + 2075 + 2587	+ 551 + 517 + 587 + 651 + 771	+ 1077 + 307 + 1351 + 2483 + 3074	+ 376 + 359 + 396 + 438 + 512	+ 1110 + 526 + 1579 + 2284 + 3045	+ 333 + 307 + 363 + 411  + 501	4 3 6 4 5	+ 25 + 90 + 109 + 14 + 29	+ 137  + 61  + 136  + 312  + 351	+ 20 + 10 - 1 + 81 + 65	$\begin{array}{ c c c } + & 25 \\ + & 25 \\ \hline - & 2 \\ + & 61 \\ + & 42 \\ \end{array}$	+ 26 + 9 - 22 + 84 + 46
266 267 268 269 270	4 05 ,,	4 4 2 1 3	128 26 ,, 128 13 ,, 127 03 ,, 126 25.5 ,, 125 53 ,,	4 4 2 1 3	5790 7780 980 3320 870	4069 4938 766 2071 640	+ 2582 + 2739 + 1026 + 1084 + 783	+ 740 + 746 + 667 + 683 + 622	+ 3156 + 3417 + 1117 + 1202 + 871	+ 494 + 494 + 442 + 450 + 417	+ 2890 + 2895 + 1481 + 1151 + 1092	+ 480 + 485 + 423 + 435 + 388	5 4 4 4	+ 24 72 35 + 18 + 201	+ 383 + 373 1 + 182 + 226	+ 99 + 73 128 + 48 + 125	+ 66 + 31 - 114 + 60 + 136	+ 94 + 84 149 + 66 + 117
271 272 273 274 275		0.2 2 2 1.5 0.0	126 14 ,, 126 59 ,, 127 00 ,,	0.2 2 4 1.5 0.0	Siao (660) 1582 2200 2749 Ternate	— 485 — 1089 — 1522 — 1755 — 38	+ 884 + 864 + 978 + 806 + 292	+ 545 + 518 + 494 + 458 + 466	+ 1036 + 979 + 1136 + 901 + 346	+ 372 + 356 + 335 + 318 + 323	+ 1267 + 1077 + 1075 + 771 + 456	+ 364 + 307 + 281 + 265 + 727	3 6 4 3	+ 197 - 83 - 179 + 43 + 137	+ 209 5 55 + 192 + 114	+ 103 112 174 + 92 + 65	+ 105 - 108 - 174 + 97 + 74	+ 82 113 162 + 115 + 68
276 277 278 279 280		0.1 1 1 0.2 2	125 19.0 ,,	0.1 1 1 0.2 2	Laboeha 5010 2530 895 4800	31 2878 1811 804 3205	+ 360 + 1318 + 1126 + 1031 + 2006	+ 413 + 419 + 422 + 464 + 439	+ 419 + 1558 + 1265 + 1201 + 2412	+ 291 + 296 + 291 + 323 + 310	+ 612 + 1196 + 1284 + 1438 + 2215	+ 242 + 255 + 258 + 299 + 282	3 3 3 3	+ 122 216 91 + 235 + 65	+ 101 + 46 + 64 + 285 + 357	+ 48 102 65 + 166 + 141	+ 54 114 66 + 163 + 113	+ 40 - 73 - 64 + 142 + 136

		les	Longitude	es			- (	Correctio	ns in 0.1	milliga	1			Anomalies in milligal					
No.	Latitude	, miles		miles	Depth	Topog	Hayfor	d-Bowie	Heisk	anen	Regi	onal	mg	Free	Mod.	Hayf.	Heisk.	Region	
	φ	п	λ	m,	meters	A-O	comp. A—O	18-1	comp. A—O	(t+c) 18-1	comp. A—O	(t+c) 18—1	"	air	Boug.	isost.	isost.	isost.	
281 282 283 284 285	3 32 S 3 29 ,, 3 49.5 ,, 4 32 ,, 5 06 ,,	2.5 1.5 0.1 3 2	0 / 124 58 E 125 43 , 126 30.0 , 126 01 ,, 127 00 ,,	2.5 1.5 0.1 3	5010 5170 1410 4130 3780	— 3211 — 3240 — 1183 — 2682 — 2516	+ 2223 + 1846 + 1017 + 1785 + 1707	+ 443 + 477 + 513 + 550 + 533	+ 2623 + 2139 + 1169 + 2071 + 1959	+ 311 + 335 + 356 + 380 + 364	+ 2597 + 2013 + 1392 + 2074 + 1998	+ 280 + 317 + 340 + 371 + 363	5 4 3 4 4	+ 35 + 4 + 48 + 15 + 32	+ 328 + 296 + 132 + 246 + 247	+ 90 + 96 + 13 + 50 + 60	+ 63 + 80 + 14 + 38 + 51	+ 68 + 95 - 7 + 39 + 48	
286 287 288 289 290	5 16 ,, 6 19 ,, 6 50 ,, 6 59 ,, 7 41.7 ,,	1 3 3 2 0.2	128 00 ,, 128 21 ,, 127 14 ,, 126 04 ,, 125 42.8 ,,	1 3 3 2 0.2	3546 4940 4780 4430 3850	— 2285 — 3323 — 3196 — 2965 — 2400	+ 1744  + 2169  + 2037  + 1923  + 1434	+ 522 + 482 + 470 + 430 + 433	+ 1994 + 2591 + 2433 + 2282 + 1630	+ 362 + 337 + 331 + 301 + 307	$^{+ 2138}_{+ 2462}_{+ 2289}_{+ 2157}_{+ 1649}$	+ 356 + 334 + 317 + 284 + 286	4 4 3 4 4	+ 42 + 22 + 26 + 31 + 10	+ 234 + 321 + 314 + 299 + 221	+ 43 + 89 + 95 + 92 + 63	+ 34 + 62 + 69 + 68 + 56	+ 20 + 75 + 85 + 83 + 56	
291 292 293 294 295	7 20 7 28 8 08.2 8 14.8 7 50	3 0.1 0.2 2	124 41 ,, 123 24 ,, 122 43.5 ,, 121 37.0 ,, 120 48 ,,	1.5 2 0.1 0.2 2	3910 3490 1527 1840 5140	- 2642 - 2346 - 992 - 1381 - 3233	+ 1776 + 1440 + 874 + 952 + 1473	+ 396 + 401 + 378 + 364 + 334	+ 2114 + 1692 + 982 + 1126 + 1762	+ 279 + 283 + 272 + 261 + 242	+ 2004 + 1585 + 1155 + 1079 + 1338	+ 254 + 256 + 244 + 230 + 207	5 5 5 5	+ 47 + 18 + 58 + 11 121	+ 286 + 227 + 133 + 126 + 182	+ 94 + 68 + 32 + 18 + 22	+ 72 + 55 + 32 + 10 + 2	+ 85 + 68 + 17 + 8 + 48	
296 297 298 299 300	8 20.0 ,, 7 50 ,, 8 02 ,, 7 19.9 ,, 6 51.3 ,,	0.2 2 2 0.3 0.1	119 49.0 ,, 118 41 ,, 117 17 ,, 113 51.6 ,, 115 42.5 ,,	0.2 1 2 0.2 0.1	80 3420 1090 45 60	141 2196 729 49 62	+ 613 + 925 + 326 - 31 + 111	+ 353 + 300 + 353 + 268 + 217	+ 729 + 1041 + 353 - 42 + 129	+ 250 + 214 + 244 + 187 + 142	+ 897 + 823 + 311 - 64 + 181	+ 204 + 166 + 204 + 136 + 101	6 6 6 4	+ 110 100 44 + 8 + 56	+ 104 + 103 + 8 1 + 52	+ 28 - 3 - 39 - 11 + 29	+ 26 - 6 - 31 - 2 + 35	+ 14 + 21 - 23 + 6 + 34	
301 302 303 304 305	6 25.5 ,, 6 25.5 ,, 6 29.2 ,, 6 19.5 ,, 5 44.1 ,,	1 1 0.2 1 0.1	116 51 ,, 117 44 ,, 118 51.2 ,, 119 49 ,, 120 27.3 ,,	1 2 0.2 1 0.1	520 340 350 1445 270	- 338 - 204 - 221 - 943 - 273	+ 175 + 177 + 290 + 536 + 381	+ 226 + 248 + 257 + 293 + 292	+ 193 + 197 + 311 + 586 + 437	+ 159 + 178 + 186 + 211 + 207	+ 180 + 226 + 439 + 608 + 477	+ 116 + 138 + 148 + 179 + 169	4 4 3 6 4	$\begin{array}{cccc} + & 41 \\ + & 43 \\ + & 47 \\ \hline - & 3 \\ + & 71 \end{array}$	+ 63 + 50 + 54 + 73 + 81	+ 35 + 21 + 14 + 8 + 31	+ 40 + 26 + 19 + 12 + 34	+ 45 + 27 + 10 + 13 + 34	
306 307 308 309 310	4 45.8 ,, 3 56 ,, 3 14 ,, 4 03.4 ,, 5 03 ,,	0.1 1.5 1.5 0.0 1	120 28.6 ,, 120 46 ,, 120 36 ,, 121 35.0 ,, 121 22.5 ,,	0.1 1.5 1.5 0.0 1	20 1683 700 Kolaka 2220	10 1087 475 4 1446	+ 109 + 193 - 123 - 34 + 611	+ 235 + 211 + 207 + 295 + 299	+ 132 + 178 165 59 + 683	÷ 163 ÷ 140 + 140 + 202 + 209	+ 176 - 2 - 362 - 2 + 535	+ 117 + 90 + 91 + 158 + 159	4 5 3 4	+ 95 - 44 - 48 + 7 + 27	+ 84 + 56 10 8 + 156	+ 62 + 24 - 9 - 19 + 81	+ 66 + 33 + 2 - 7 + 82	+ 67 + 56 - 46 - 8 + 102	
311 312 313 314 315	5 58 ,, 5 27.3 ,, 6 25 ,, 5 58 ,, 6 12 ,,	5 0.0 1 0.2 2.5	121 43 ,, 122 37.0 ,, 122 58 ,, 124 12 ,, 125 10 ,,	1.5 0.0 1 0.2 2.5	2555 Boeton 2295 820 3845	— 1607 — 28 — 1497 — 657 — 2535	+ 911 + 340 + 1038 + 947 + 1683	+ 341 + 401 + 407 + 465 + 491	+ 1045 + 390 + 1165 + 1051 + 1935	+ 241 + 285 + 281 + 328 + 342	+ 977 + 586 + 1277 + 1413 + 1964	+ 206 + 251 + 257 + 314 + 334	4 3 4 4 5	+ 34 + 69 + 21 + 81 — 15	+ 174 + 47 + 145 + 115 + 205	$egin{pmatrix} + & 70 \\ - & 2 \\ + & 26 \\ + & 6 \\ + & 21 \end{bmatrix}$	+ 66 + 4 + 26 + 9 + 11	+ 76 - 12 + 17 - 26 + 9	
316 317 318 319 320	5 44 ,, 5 07 ,, 4 32 ,, 3 51.5 ,, 2 51 ,,	2 2 2 1 2.5	126 02 ,, 125 06 ,, 124 12 ,, 123 15 ,, 123 43 ,,	2 2 2 1 2.5	4130 3150 5080 1161 4860	— 2633 — 2109 — 3343 — 830 — 3149	$egin{array}{c} + \ 1802 \\ + \ 1670 \\ + \ 1979 \\ + \ 866 \\ + \ 1824 \\ \hline \end{array}$	+ 530 + 526 + 457 + 386 + 357	$^{+}$ 2076 $^{+}$ 1944 $^{+}$ 2370 $^{+}$ 972 $^{+}$ 2193	+ 367 + 364 + 317 + 265 + 245	+ 2130 + 2043 + 2128 + 1203 + 1924	+ 364 + 363 + 303 + 233 + 216	4 4 4 4	+ 14 + 53 + 19 + 95 — 11	+ 241 + 228 + 323 + 155 + 282	$^{+\  \   44}_{+\  \   44}_{+\   110}_{+\  \   53}_{+\  \   86}$	+ 33 + 33 + 85 + 54   + 60	+ 28 + 23 + 110 + 34 + 90	
321 322 323 324 325	2 49 ,, 1 45 ,, 1 25.0 ,, 0 40 ,, 0 23.5 ,,	2 2 0.5 1.5 0.5	122 27 ,, 122 15 ,, 123 38.0 ,, 124 36 ,, 123 06.0 ,,	2 2 0.5 1.5 0.5	2572 . 1080 60 2468 2040	— 1524 — 701 — 63 — 1720 — 1295	+ 604 + 214 + 377 + 1138 + 624	+ 319 + 298 + 404 + 431 + 388	+ 660 + 215 + 404 + 1345 + 716	+ 223 + 208 + 285 + 303 + 265	+ 555 + 161 + 607 + 1268 + 651	+ 174 + 163 + 247 + 257 + 223	4 4 4 4	- 47 - 21 + 73 - 183 - 46	+ 88 + 33 + 55 - 37 + 61	+ 13 - 2 + 1 - 168 - 18	+ 17 + 7 + 10 - 174 - 15	+ 33 + 17 - 6 - 164 - 4	
326 327 328 329 330	0 37.0 ,, 0 45 ,, 0 35 ,, 0 01 ,, 0 12 N	0.5 1 1 1.5 1.5	122 09.5 ,, 121 18 ,, 120 29 ,, 121 15 ,, 122 18 ,,	0.5 1 1 1.5 1.5	1010 1750 1720 1960 2325	811 1160 1151 1270 1487	+ 287 + 374 + 368 + 480 + 528	+ 284 + 251 + 247 + 322 + 406	+ 263 + 396 + 397 + 536 + 558	+ 196 + 170 + 171 + 219 + 282	+ 273 + 240 + 227 + 374 + 421	+ 143 + 115 + 122 + 178 + 238	4 3 4 4 4	+ 1 - 30 - 42 + 17 - 78	$ \begin{vmatrix} + & 68 \\ + & 74 \\ + & 61 \\ + & 126 \\ + & 47 \end{vmatrix} $	+ 15 + 24 + 12 + 64 - 23	+ 36 + 29 + 16 + 68 — 13	+ 40 + 50 + 38 + 89 + 5	
331 332 333 334 335		0.0 1 1 3 1	123 03.4 ,, 124 00.5 ,, 124 38 ,, 125 43 ,, 125 46 ,,	0.0 1 1 3 3	Gorontalo 3600 1245 2230 1675	— 158 — 2408 — 1004 — 1470 — 1189	+ 382 + 1197 + 787 + 913 + 806	+ 451 + 409 + 444 + 450 + 482	+ 428 + 1429 + 911 + 1038 + 906	+ 309 + 285 + 313 + 313 + 336	+ 583 + 1110 + 957 + 1038 + 926	+ 273 + 233 + 271 + 272 + 289	3 4 4 4 4	$^{+\  \   91}_{-\   107} \\ ^{+\   117}_{-\   83} \\ ^{+\   24}$	+ 80 + 111 + 190 + 37 + 114	+ 24 - 27 + 94 - 72 + 14	+ 33 - 38 + 95 - 71 + 19	+ 21 0 + 95 - 67 + 21	
336 337 338 339 340	1 18.0 ,, 1 58 ,, 2 49 ,,	0.5	124 02.0 ,, 123 15 ,,	1 0.0 0.5 2 1.5	940 Menado 1830 5570 5178	— 744 — 59 — 1461 — 3593 — 3491	+ 841 + 553 + 1032 + 2150 + 2430	+ 528 + 519 + 509 + 497 + 542	+ 933 + 618 + 1188 + 2590 + 2879	+ 351 + 363 + 351 + 328 + 374	+ 1148 + 968 + 1169 + 2333 + 2857	+ 329 + 328 + 326 + 316 + 369	4 2 5 4 4	+ 136 + 157 + 75 - 21 + 31	+ 178 + 130 + 188 + 307 + 343	+ 74 + 56 + 67 + 74 + 83	+ 82 + 65 + 67 + 46 + 55	+ 63 + 34 + 72 + 73 + 58	
341 342 343 344 345	2 06 ,, 1 36 ,, 0 53.5 ,,	$\begin{vmatrix} 2 \\ 2 \end{vmatrix}$	120 46.5 ,, 119 46 ,, 119 03 ,, 119 01.0 ,,	1.5 0.3 2 1 0.5	5440 725 5180 860 448	— 3676 — 661 — 3279 — 673 — 350	+ 2357 + 736 + 1941 + 820 + 548	+ 472 + 413 + 313 + 262 + 251	$^{+\ 2828}_{+\ 814}_{+\ 2311}_{+\ 988}_{+\ 637}$	+ 325 + 288 + 217 + 185 + 175	+ 2668 + 1003 + 2105 + 1104 + 774	+ 324 + 273 + 203 + 164 + 154	4 4 5 5	$egin{array}{cccc} -&&1\ +&141\ -&49\ +&69\ +&106 \end{array}$	+ 334 + 180 + 259 + 120 + 126	+ 84 + 92 + 53 + 28 + 61	+ 51 + 97 + 26 + 19 + 60	+ 67 + 80 + 48 + 10 + 48	
346 347 348 349 350	0 42 ,, 0 51.5 ,,	1.5 0.5	118 26 ,, 117 43.0 ,,	1 0.0 1.5 0.5 0.0	2432 Donggala 2380 100 Balikpapan	— 1544 — 20 — 1586 — 76 — 11	+ 784 + 128 + 850 + 277 — 12	+ 224 + 196 + 124 + 130 + 113	+ 884 + 124 + 983 + 322 — 20	+ 161 + 134 + 82 + 91 + 77	+ 789 + 248 + 862 + 438 - 9	+ 125 + 95 + 48 + 62 + 57	6 3 4 4 3	- 24 + 74 - 18 + 96 + 19	+ 118 + 66 + 136 + 97 + 14	+ 30 + 44 + 43 + 63 + 10	+ 26 + 50 + 34 + 62 + 14	+ 39 + 42 + 50 + 54 + 15	

		es				Corrections in 0.1 milligal											Anoma	ilies in r	nilligal	
No.	Latitude	miles		miles	Depth	Topog	Hayfo	d-Bo	wie	Heisk	ane	n	Regi	onal	m <sub>g</sub>	Free	Mod.	Hayf.		
	<i>T</i>	m g	ì.	n,	meters	A—O	comp. A—O	18-		comp. A—O		+ c) 81	comp. A—O	(t+c) 18—1	, s	air	Boug.	isost.	Heisk. isost.	Region. isost.
351 352 353 354 355	1 48 S 2 10 ,, 2 34.5 ,, 3 11 ., 3 50 ,,	2 0.2 2 1.5	117 44 E 118 23 , 118 46.5 , 118 04 ,,	2 2 0.2 2 1.5	1610 2220 1611 75 1990	— 1198 — 1481 — 1019 — 69 — 1356	+ 573 + 681 + 290 + 251 + 616	+ 1+ 1+ 1+ 1	117 142 162 142 165	+ 640 + 682 + 297 + 303 + 716	+++++	79 95 110 96 112	+- 551 + 603 +- 183 +- 394 + 527	+ 5: + 6: + 7: + 6: + 7:	1 4 1 4 3 4	- 1 - 30 - 12 + 85 - 45	+ 112 + 82 + 86	+ 50 + 36 + 44 + 52 + 12	+ 47 + 40 + 49 + 52 + 8	+ 59 + 52 + 64 + 46 + 30
356 357 358 359 360	4 00.6 ., 5 07.7 ,, 4 52 ,, 4 50 ,, 4 51.2 ,,	0.0 0.0 1 2 0.5	119 37.1 , 119 24.4 ,, 118 22 ,, 117 18.5 ,, 116 05.2 ,,	0.0 0.0 1 1 0.5	Pare Pare Makassar 1795 242 60	— 2 — 10 — 1183 — 206 — 60	- 17 + 47 + 559 + 268 + 29	+ 1	203 252 168 169 162	- 25 - 67 + 624 + 311 + 32	+++++	139 180 113 119 110	- 45 + 124 + 550 + 319 + 38	+ 101 + 143 + 76 + 84 + 77	2 3 5 4 4 4	+ 40 + 48 + 4 + 57 + 32	+ 35 + 115 + 69	+ 22 + 19 + 50 + 34 + 19	+ 29 + 38 + 49 + 35 + 24	+ 35 + 22 + 60 + 37 + 26
361 362 363 364 365	5 10 ,, 5 28 ,, 6 07 ,, 6 23 ,, 5 43 ,,	1 1 2 1	114 53.5 ,, 113 58.5 ,, 113 28 ,, 112 12 ,, 111 00 ,,	1 1 2 1	30 60 75 60 55	— 27 — 59 — 73 — 53 — 52	+ 13 + 24 + 25 + 5 + 22	+ 1 + 1 + 1	147 148 170 193 163	$\begin{array}{cccc} + & 16 \\ + & 28 \\ + & 29 \\ + & 7 \\ + & 27 \end{array}$	+++++	100 100 113 129 108	+ 17 + 29 + 26 - 7 + 24	+ 64 + 71 + 83 + 66	4 l 4 l 4	+ 44 + 30 + 33 + 44 + 58	+ 30 + 33 + 41	+ 31 + 19 + 21 + 30 + 45	+ 35 + 23 + 26 + 36 + 50	+ 39 + 27 + 31 + 42 + 54
366 367 368 369 370	5 32 ,, 5 18 ,, 5 30 ,, 5 35.5 ,, 4 51.1 ,,	2 2 1.5 0.3 0.1	107 18 ,,	2 2 1.5 0.3 0.1	55 45 40 1050 220	- 61 - 52 - 41 - 720 - 154	+ 26 + 20 - 2 + 401 + 86	· · · · 1   + · 2   + · 4	164 173 219 419 390	$\begin{array}{cccc} + & 29 \\ + & 25 \\ + & 1 \\ + & 449 \\ + & 89 \end{array}$	+++++	110 113 146 280 263	+ 32 + 24 - 15 + 424 + 102	+ 69 + 69 + 230 + 200	4 3 4 4	+ 21 + 30 + 35 - 3 + 26	+ 28 + 30 + 46	+ 8 + 16 + 17 13 6	+ 13 + 21 + 24 - 4 + 6	+ 17 + 26 + 31 + 4 + 11
371 372 373 374 375		0.0 1 1.5 2.5 4	101 17 ,,	0.0 1 1.5 2.5 4	Benkoelen 1105 50 5890 4972	- 7 - 728 - 53 - 3765 - 3383	- 76 + 340 - 633 - 2197 + 2407	+ 4	355 455 518 644 822	$\begin{array}{rrr} -&102\\ +&354\\ +&718\\ +&2622\\ +&2812 \end{array}$	+++++	238 304 345 427 543	- 99 + 352 + 1000 + 2391 + 2878	+ 183 + 263 + 303 + 403 + 536	1 4 3 4 3 4	+ 61 44 72 81 50	+ 3 + 46 + 255	+ 34 - 51 - 38 + 11 + 65	+ 48 - 37 - 29 - 9 + 53	+ 53 - 32 - 54 + 16 + 47
376 377 378 379 380	4 43 ,, 3 54 ,,	4 3 2 2 1.5	98 02 ,, 97 16 ,, 96 36 ,,	4 3 2 2 1.5	5520 5520 4950 5070 4220	— 3695 — 3672 — 3364 — 3390 — 2960	+ 2489 + 2490 + 2392 + 2340 + 2231	+ 8	918 905 891 864 746	+ 2946 + 2932 + 2792 + 2748 + 2601	+++++	595 589 583 566 494	+ 2903 + 2918 + 2857 + 2755 + 2707	+ 593 593 583 + 560 + 486	4 4	+ 19 + 4 + 31 + 19 + 85	+ 312 + 309 + 302	+ 48 + 32 + 39 + 38 + 83	+ 34 + 19 + 30 + 27 + 72	+ 39 + 20 + 24 + 26 + 62
381 382 383 384 385	2 34 ,, 1 40.9 ,, 1 20 ,, 1 00.1 ., 1 44.3 N	1.5 0.0 1 0.0 0.0	99 13.6 ,, 99 48 ,,	1.5 0.0 1 0.0 0.0	5311 Kantorei B. 1765 Padang Sibolga	— 3508 — 13 — 1158 — 18 — 18	÷ 2030 + 429 + 394 — 135 — 293	+ 3 + 2	519 442 359 262 228	+ 2427 + 485 + 435 - 178 - 368	.++++	414 294 242 176 154	+ 2168 + 716 + 270 - 141 - 384	+ 393 + 256 + 194 + 122 + 106	3 4 3	- 50 + 64 - 57 + 6 - 6	+ 40 + 39 - 4	+ 36 22 16 5 + 2	+ 17 - 13 - 9 + 8 + 17	+ 45 32 + 12 + 10 + 24
386 387 388 389 390	1 33 1 17.7 1 21.5 0 58.5 0 20	1 0.0 0.5 1 2	97 03.0 ,, 96 31 ,,	1 0.0 0.5 1 2	705 G. Sitoli 488 5280 4092	— 469 — 8 — 355 — 3454 — 2777	+ 105 + 197 + 615 + 1881 + 2112	+ 3	325 353 407 480 629	+ 91 + 200 + 699 - 2260 + 2444	++++	216 238 272 324 425	+ 55 + 356 + 920 + 1930 + 2576	+ 170 + 199 + 241 + 295 - 406	3 4 4	- 14 + 10 + 55 - 76 + 83	- 9 + 66 + 240	10 44 12 + 33 + 87	$\begin{array}{c c} + & 2 \\ - & 33 \\ - & 7 \\ + & 11 \\ + & 74 \end{array}$	+ 10 - 45 - 26 + 47 + 63
391 392 393 394 395	0 18 N 1 21 ., 2 52 .,	3 2 2 1 1	93 14 ,, 92 18 ,, 92 01 ,,	3 2 2 1	4590 4530 4410 4180 4390	3104 3066 2972 2815 2971	+ 2172 + 2137 + 2086 + 1923 + 2047	+ 7 + 6	784 300 773 599 538	$^{+\ 2539}_{+\ 2493}_{+\ 2433}_{+\ 2401}$	+++++	520 529 517 472 435	+ 2570 + 2534 + 2474 + 2257 + 2402	+ 513 + 518 + 499 + 446 + 409	4 4 4	+ 25 - 11 - 6 + 11 - 15	+ 244 + 241 + 248	+ 40 + 2 + 5 + 30 + 14	$\begin{array}{c c} + & 30 \\ - & 7 \\ - & 4 \\ + & 21 \\ - & 2 \end{array}$	+ 27 10 6 + 22 + 1
396 397 398 399 400	4 33 5 12 6 13 .,	1 2 1.5 2	93 32 ,, 94 12 ,, 96 02 ,,	1 1 2 1.5 2	4480 1380 2555 1095 1305	2890 1087   1641 747 876	+ 1883 + 1301 + 1026 + 524 + 546	+ 5 + 4 + 2	584 531 457 259 219	+ 2185 + 1506 + 1160 + 610 + 627	+++++	404 365 318 184 153	+ 2181 + 1767 - 1169 + 591 + 603	+ 371 + 331 + 279 + 140 + 111	4 4	57 + 54 123 +- 31 9	+ 130 + 13 + 92	$ \begin{array}{r}  - 15 \\  - 20 \\  - 107 \\  + 27 \\  + 2 \end{array} $	- 27 - 24 - 107 + 26 0	- 23 - 47 - 104 + 33 + 7
401 402 403 404 405	5 35 3 51.5 ,. 3 25.7 ,, 2 45.8 ,, 2 12.3 ,,	2 0.0 0.5 0.5 0.3	99 42.3 ,, 101 09.4 ,,	2 0.0 0.5 0.5 0.3	300 Belawan 40 40 40	— 203 — 10 — 36 — 36 — 33	+ 147 - 106 - 28 - 34 - 46	÷ 1	182 131 90 72 75	+ 175 - 120 - 27 - 38 - 56	+++++	123 84 55 41 45	- 154 - 192 - 61 - 68 - 81	+ 83 46 21 + 16 22	2 4	- 4 - 1 + 19 + 25 + 18	- 5 + 20 + 27	- 17 - 2 + 16 + 25 + 18	- 14 + 4 + 20 + 28 + 22	- 7 + 15 + 27 + 34 + 27
406 407 408 409 410	1 09.3 ,, 1 19.3 ,, 0 45 ,, 0 41.1 ,, 0 25.5 \$	0.0 0.5 1 0.2 1	106 21 ,, 107 24.8 ,,	0.0 0.5 1 0.2	P. Samboe 50 50 50 50 50	— 16 — 49 — 44 — 48 — 44	- 4 + 16 + 24 - 21 + 21	+ + + + + + + + + + + + + + + + + + + +	76 81 81 87 86	- 3 + 20 + 28 - 26 + 26	+++++	48 54 53 57 57	9 + 18 + 32 + 27 + 26	+ 29 + 36 + 36 + 38 + 38	4 5 4	+ 26 + 21 + 34 + 30 + 41	+ 22 + 35 + 31	$\begin{array}{cccc} + & 20 \\ + & 16 \\ + & 28 \\ + & 24 \\ + & 35 \end{array}$	+ 23 + 18 + 30 + 26 + 37	+ 26 + 21 + 32 + 28 + 39
411 412 413 414 415		1 0.5 0.3 0.1 1	106 00.0 ,, 105 08.5 ,, 104 46.2 ,,	1 0.5 0.3 0.1 1	40 30 30 30 Palembang 20	- 46 - 27 - 24 + 4 - 14	- · 16  - 9  - 0  - 14  - 4	+ + 1 + 1	91 98 113 145 143	19 11 0 16 7	+++	60 65 73 93 95	+ 18 + 11 - 4 - 24 + 3	+ 38 + 41 + 45 + 55 + 59	3 3	+ 33 + 30 + 46 + 53 + 46	+ 29 + 44	+ 27 + 22 + 37 + 40 + 33	+ 30 + 25 + 41 + 45 + 37	+ 32 + 28 + 44 + 50 + 41
416 417 418 419 420	2 19.1 ,, 3 00 ,,	0.5 0.0 0.7 1.5	107 36.2 108 39.3 ,, 109 06	0.5 0.0 0.7 1.5	30 T. Pandan 40 25 40	- 27 - 6 - 39 - 25 - 45	- 3 - 2 - 5 - 12 - 16	J. 1	126 110 75 98 117		+ + + + + + + + + + + + + + + + + + + +	85 73 48 63 76	- 2 + 6 - 3 + 13 + 18	- - 53 - - 45 - - 30 - - 46	3 4	+ 35 + 27   41   + 19   + 31	+ 23 + 42 + 18	+ 25 + 17 + 37 + 10 + 22	+ 29 + 20 + 40 + 14 + 26	+ 33 + 22 + 42 + 16 + 29
														_						

_		es.		es		1	(	Correctio	ns in 0.1	milliga	1				Anoma	lies in n	nilligal	
No.	Latitude	miles	Longitude	miles	Depth	Topog	Hayfor	d-Bowie	Heisk	anen	Regi	onal	mg	Free	Mod.	Hayf.	Heisk.	Region
	THE E	λ	m,	meters	AO	comp. AO	(t·c) 18—1	comp. A—O	(t  -c) 18—1	comp.	(t : c) 181	5	air	Boug.	isost.	isost.	isost.	
421 422 423 424 425	4 22 ,, 4 44 ,, 5 37.9 ,, 1 15.8 N	2 2 1.5 0.5 0.0	112 26 ,, 112 33.7 ,,	2 2 1.5 0.5 0.0	35 50 60 65 Singapore	41 50 59 60 13	+ 16 + 19 + 23 + 26 - 32 + 265	+ 108 + 111 + 113 + 150 + 77	+ 19 + 25 + 26 + 29 - 62	+ 69 : 72 + 73 - 99 : 50	+ 18 : 23 + 27 34 50 + 412	+ 45 45 + 45 + 62 + 29	4 4 4 4 3	+ 35 + 31 + 41 + 21 + 35 + 15	+ 35 + 32 + 42 + 21 + 33	+ 27 + 23 + 33 + 9 + 32	+ 30 + 26 + 37 + 14 + 38	+ 33 29 + 40 17 38
427 428 429 430	47 44 ,, 46 21 ,, 44 34 ,,	1.5 1 1 1	9 21 ,, 12 49 ,, 16 37 ,,	1.5 1 1 2	3650 4040 3780 4550	2505 - 2863 - 2683 - 3107	+ 1430 + 2077 + 1998 2166	+ 447 + 605 + 781 + 780	1654 2385 2283 2499	+ 259 : 321 + 415 - 516 + 518	+ 412 + 1581 + 2554 + 2484 + 2631	290 - 394 - 513 + 502	4 8 4 4	- 72 + 73 + 52 + 21	+ 150 320 269 281	9 + 91 + 42 + 37	19 + 79 40 + 30	9 + 65 21 18
431 432 433 434 435	42 18 ,, 40 45 ,, 39 55 ,,	2 2 1 1.5	20 30 ,, 22 09 ,,	2 2 1 1.5 1	4100 3700 4290 4110 3900	2781 2591 2792 2814 2645	+ 1957 + 1827 + 1948 + 1918 + 1771	+ 781 - 765 : 735 - 721 - 704	+ 2352 + 2105 + 2250 + 2230 + 2039	+ 517 + 510 + 493 - 482 + 471	÷ 2380 ÷ 2205 ÷ 2328 ÷ 2347 ÷ 2109	+ 497 + 483 + 456 + 443 + 430	3 5 4 4 3	- - 50 + 45 - - 9 - - 15 - - 36	+ 278 + 256 + 243 + 252 + 258	+ 54 + 45 + 20 + 33 + 53	+ 51 + 43 + 14 + 25 + 50	+ 40 + 35 + 10 + 17 + 47
436 437 438 439 440	37 43.92,, 37 16 ,, 35 58 ,,	1 0.0 1 1.5 1.5	26 06 ,, 27 20 ,,	1 0.0 I 1 1.5 1.5	3480 P. Delgada 2440 3530 3260	— 2330 — 63 — 1604 — 2407 — 2275	+ 647 + 647 950 + 1597 + 1667	+ 693 + 680 + 665 + 680 + 689	+ 1659 + 745 + 1037 + 1842 + 1898	463 : 456 446 456 461	+ 1675 + 1042 + 1113 + 1903 + 2063	+ 420 + 402 + 392 + 410 + 418	3 4 4 4 3	- 6 + 152 + 11 + 25 + 35	+ 185  - 118  - 132  + 225  + 221	+ 13 + 26 + 10 + 38 + 27	+ 15 + 38 23 + 36 27	+ 18 + 14 + 21 + 34 + 14
441 442 443 444 445	35 51 ,, 36 12 ,, 36 37 ,,	1.5 1 1 1 1.5	30 19 ,, 31 18 ,, 32 23 ,,	1.5 2 2 1 1.5	3600 3220 2910 2520 1750	— 2470 — 2189 — 1931 — 1778 — 1261	+ 1693 + 1480 + 1334 + 1275 + 1224	+- 683 +- 676 +- 670 +- 664 +- 699	-1- 1941 - - 1677 1498 - - 1455 - - 1414	+ 458 + 454 + 447 + 444 + 468	+ 2037 + 1795 + 1630 + 1550 + 1607	+ 411 + 404 + 398 + 392 + 419	4 3 3 6 6	+ 33 36 + 22 + 51 + 48	+ 239 214 175 190 132	+ 42 + 39 + 15 + 35 - 18	+ 40 + 42 + 21 + 39 14	+ 35 + 35 + 12 + 35 - 23
446 447 448 449 450	38 04 ,, 39 07 ,, 39 57 ,,	1.5 1.5 1.5 1.5 1.5	36 04 36 09 35 36	1.5 1.5 1.5 1.5 1.5	2990 3740 4170 4620 4290	— 2092 — 2585 — 2874 — 3172 — 2938	1458   1763   + 1954   + 2136   2038	+ 726 + 756 + 770 + 757 + 746	+ 1671 - 2019 - 2247 + 2494 - 2374	+ 482 + 500 : 510 - 505 + 498	+ 1762 + 2122 + 2363 + 2545 + 2475	442 463 481 471 464	3 6 7 3 5	÷ 28 ÷ 27 ÷ 35 ÷ 15 ÷ 27	+ 193 + 239 + 274 + 285 + 274	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	÷ 22 + 34 + 47 - 32 ÷ 34	+ 17 + 27 + 38 + 31 + 27
451 452 453 454 455	42 15 ,, 42 10 ,,	1.5 2 1.5 1 1.5	33 19 31 51 30 25	1.5 2 1.5 1 1.5	4100 4010 3130 2820 2470	— 2799 — 2703 — 2173 — 1889 — 1546	1933 1838 1517 1301 1139	: 731 	+ 2224 + 2112 1728 1479 1291	- - 489 481 469 458 -  449	+ 2338 + 2204 + 1812 + 1578 + 1419	+ 457 + 444 + 430 + 416 + 403	7 3 3 3 2	+ 35 + 42 + 9 - 33 + 34	+ 269 + 268 + 183 180 + 148	- - 48 - - 57 - - 5 - - 24 - - 8	+ 44 + 53 + 7 - 28 + 15	+ 35 + 48 + 2 - 23 + 6
456 457 458 459 460	41 08 ,, 40 30 ,,	1.5 1.5 1.5 1 1.5	26 37 25 18 24 09 .,	1.5 2 1.5 1 1.5	2670 3120 3640 4050 4410	1848 2125 2410 2726 3054	1270 1439 1594 1815 2105	+ 647 + 629 + 666 + 695 + 760	+ 1432 + 1621 + 1810 + 2191 + 2454	+ 437 + 426 + 448 + 465 : 507	+ 1534 + 1732 + 1913 + 2159 + 2516	- 393 - 377 - 408 - 429 - 482	4 3 3 3	+ 34 + 42 + 41 + 28 + 6	+ 179 + 217 - 241 + 258 + 263	+ 27 + 48 + 56 + 50 + 25	+ 32 + 50 + 56 + 35 + 15	26 + 44 - 50 + 42 + 12
461 462 463 464 465	36 59 ,, 35 50 ,, 34 45 ,,	1.5 3 1.5 1.5 2	21 45 ,, 21 33 ,, 21 32 ,,	1.5 2 1.5 1.5 2	3720 4120 5130 5320 5470	2813 2866 3446 3591 3687	+ 2011 - 2020 - 2340 - 2484 - 2518	776   789   809    825  + 841	+ 2313 + 2299 + 2734  - 2888 + 2937	516 523 537 544 553	-  2473   2462   2797  - 3003  - 3016	+ 495 + 503 - 517 + 530 + 541	7 7 3 3 4	+ 51 + 43 - 16 - 7 - 23	÷ 283 · 279 + 277 + 299 + 292	+ 54 + 49 + 14 + 21 + 10	+ 49 + 47 + 2 + 9 - 3	- 35 - 33 - 3 - 1 - 10
466 467 468 469 470	33 04 , 32 48 ,,	1.5 1 1 0.0 1.5	19 06 ,, 17 56 ,, 16 54.96,,	1.5 2.5 2.5 0.0 1.5	5040 4000 3250 Funchal 4070	3416 2805 2242 231 2606	+ 2355 + 2016 + 1627 + 1121 + 1651	+ 794 + 772 + 722 + 692	+ 2736 + 2315 + 1821 + 1259 + 1851	→ 542 → 528 → 515 → 485 → 463	2844  - 2476  - 2040  - 1807  - 1956	+ 528 + 511 + 495 - 466 + 445	3 7 3 5	- 6 + 47 + 80 + 230 - 2	+- 283 +- 276 +- 255 +- 206 +- 214	+ 18 + 47 + 64 + 69 + 24	- 8  - 43  - 71  - 79  - 27	- 2 + 29 - 51 + 26 + 19
471 472 473 474 475	33 04 ,, 33 20 34 22 35 25 36 30	1.5 1.5 1 1	13 50 13 27	1.5 1.5 1 1	4220 4520 4420 4940 2790	2852 2900 2994 3164 2160	+ 1907 + 1915 + 2004 + 1997 + 1733	+ 642 + 597 + 593 + 589 + 586	+ 2204 + 2165 + 2327 + 2312 + 2011	+ 438 + 412 + 410 + 406 + 404	+ 2269 + 2316 + 2373 + 2324 - 2166	+ 414 + 389 + 390 + 387 + 384	4 3 5 3 3	- 41 - 18 - 16 + 119	+ 246 + 210 + 242 + 262 + 297	+ 32 - 2 + 22 + 42 + 103	+ 8 + 8 + 29 + 93	+ 19 - 21 + 5 + 29 + 80
476 477 478 479 480	38 30 ,, 39 32 ,, 40 42 ,,	1 1 1 1	12 00 ,, 11 32 ,, 12 11 ,,	1 1 1 1 1	5190 4890 4440 5360 5360	— 3441 — 3355 — 3139 — 3555 — 3559		+ 585 + 581 + 581 + 628 + 677	+ 2630 + 2667 + 2515 + 2730 + 2709	+ 406 + 403 + 402 - 431 + 459	+ 2588 2686 2548 + 2708 + 2660	+ 385 + 383 - 383 + 420 + 453	4 4 4 6 4	- 57 - 34 - 33 - 25 - 7	+ 249 + 263 243 + 289 304	+ 6 + 17 + 9 + 36 + 52	- 17 - 6 - 11 + 14 + 32	- 10 - 5 - 12   18 + 38
481 482 483 484 485 486	43 47 ., 44 42 ., 45 34 ., 46 42 .,	1 1.5 1.5 1 1	11 34 ,, 10 25 ,, 09 19 ,,	1 1.5 1.5 1 1 1	890 5060 4960 4830 4600	- 877 - 3406 - 3220 - 3306 - 3111 - 188	+ 1448 + 2120 - 2113 - 2224 + 2040 - 366	+ 651 + 619 + 562 + 509 + 418 + 331	+ 1614 + 2504 + 2440 + 2587 + 2397 + 394	+ 443 + 421 389 + 359 300 + 239	+ 2086 2425 2514 2653 2403 607	+ 431 + 402 + 377 + 352 + 280 + 216	3 4 8 4 3 3	+ 123 - 63 - 11 - 6 - 18 + 44	+ 168 + 237 + 295 ÷ 301 + 265 + 41	+ 1 + 4 - 65 + 63 + 47 - 7	+ 5 - 15 + 50 + 42 + 23 0	- 41 - 5 + 44 + 36 + 25 - 20
				:														

## § 3. Pairs of Stations a few miles apart in irregular topography.

In a few cases during the expeditions in the Netherlands East Indies a second observation was made at a short distance from the first observation. This was done when the topography was particularly irregular or when unexpected topographic features had been found by the echo-soundings during the submergence. In this way the writer hoped to reduce the uncertainty of the topographic reductions, that would inevitably result from these irregularities because it was out of the question to make a detailed sounding investigation of the surrounding area. At the same time the results might give some idea of the kind of errors, brought about by such causes.

Pairs of observations were made at the stations 220 (25), 223 (28), 236 (41), 286 (93), 293 (100) and 381 (189). The numbers in brackets are those given during the expeditions and used in chapter V of Vol I of this publication in which the report of these expeditions is given. In this report No 220 (25) was classed by mistake under the control stations with regular topography where the two results could be compared without any further reduction.

In the lists of results at the end of Vol I and in the previous §, the pairs of stations have been combined in single stations, because it would have no value to plot them separately. In these lists the positions, the topographic and isostatic corrections and the anomalies for these combined stations are the means of those quantities for each station of the pair separately.

The following list gives in the same way as the list of the previous §:

- 1. The number of the station,
- 2. The Latitude of the station,
- 3. The Longitude of the station,
- 4. The depth of the sea in meters,
- 5. The Correction for the Topography of Zones A-O in 0.1 milligal,
- 6. The Hayford-Bowie Correction for the Compensation of Zones A-O in 0.1 milligal,
- 7. The Hayford-Bowie Correction for the Topography and Compensation of Zones 18—1 in 0.1 milligal,
- 8. The Heiskanen Correction for the Compensation of Zones A-O in 0.1 milligal,
- 9. The Heiskanen Correction for the Topography and Compensation of Zones 18—1 in 0.1 milligal,
- 10. The Regional Correction for the Compensation of Zones A—O in 0.1 milligal,
- 11. The Regional Correction for the Topography and Compensation of Zones 18—1 in 0.1 milligal,
- 12. The Free-air Anomaly in milligal,
- 13. The Modified Bouguer Anomaly in milligal,
- 14. The Hayford-Bowie Isostatic Anomaly in milligal,
- 15. The Heiskanen Isostatic Anomaly in milligal,
- 16. The Regional Isostatic Anomaly in milligal.

						0.1	milliga	1			A	nomal	ies in	milliq	gal
$N^0$ .	Latitude	Longitude	Depth meters		Hayf. B	owie	Heiska	nen	Regional		Free-	Mod.	Hayf.	Heisk.	
			meters	ropog.	A-O	181	A-O	18—1	A-O	18—1	Air	Boug.	Bow.	i ieisk.	Keg.
220 A 220 B	8° 32.0 S 8 28.4 " S of Tanis	130 58.9 ,,													
	7 06 5 S 7 04.0 ,, NW of Ta	130 22 8 ,,			+1587 +1690										
	4 05.0 S 4 09.5 ,, S coast of		20 660	- 16 - 210	+ 260 + 375										
286A 286B	5 15,0 S 5 18.0 ,,   <b>WSW of</b>	128 02.0 "	3748 3345	-2328 -2242	+1739 +1750	+527 +517	+1978 +2011	+365 +359	+2151 +2126	+359 +352	+ 28 + 5 <b>4</b>	+225 +243	+ 34 + 52	+ 26 + 41	+10 +30
293A 293B	8 07.1 S   8 09.4 ,,   <b>NE coast o</b>	122 <del>1</del> 3.8 "	1695 1360	-1098 - 887	+ 886 + 863	+376 +380	+ 993 + 971	+270 +273	+1160 +1150	+242 +245	+ 47 + 68	+133 +132	+ 31 + 32	+ 31 + 32	+17 +17
381 A 381 B	2 36.0 S 2 32.5   WSW of	98 32.0 .,	4860 5762	-3397 -3619	+2052 +2008										

The relative position of the two stations of a pair is considerably more accurate than each position in itself. Its mean error may be estimated at one or two tenths of a sea-mile.

The comparizon of the results for each pair is interesting and it certainly may give an idea about the differences of gravity that we may expect over short distances, but it does not give much hold on the question of the error that we may expect in corrections for topography in such irregular areas, because, as the map shows, most of these stations are situated, by chance, near to the strip of strong negative anomalies, i.e. in areas where the gradient of the anomalies must be great. So the principal part of the differences may probably be attributed to these gradients and it may be noticed that, save for No 381, the differences are in the same sense as the gradient that may be expected in that area.

Only two stations are situated in a more regular field, i.e. Nos 286 and 293, and 293 shows indeed only a slight difference in the anomalies. So our view is confirmed. Station 286 shows a greater difference, which is a curious result in connection with the surrounding anomalies. It is difficult to say whether this result and that of No 381 is caused by some unknown topographic feature in the neighbourhood, which would not be surprising in these areas of very irregular topography, or whether it is a local anomaly that is caused by a hidden mass-irregularity.

Resuming these considerations, the writer does not think that much can be concluded from these results, neither about eventual errors in topographic reductions, nor about the question which method of isostatic reduction gives the best approximation to the actual state of the crust for each of these stations.

## CHAPTER IV.

## Discussion of the Results.

## § 1. General Remarks.

The gravity results of the nearly five-hundred stations at sea confirm the result found by Hecker in the beginning of this century, that, roughly speaking, the Earth's crust under the oceans is in isostatic equilibrium with the crust in the continents. The anomalies after isostatic reduction seldom exceed the tenth part of the values that ought to have been found when the mass-defects of the oceans were not compensated. In many cases even the isostatic anomalies are positive, that is to say there is over-compensation. So the first conclusion that can be drawn is a decided confirmation of the principle of isostasy.

This has already more than once been pointed out by the well known supporter of this principle, William Bowie, in discussing the results of the gravity determinations at sea. The writer wishes to lay stress on this conclusion, because in his opinion, the numerous results of this publication are proper to dispell any doubt that might still exist about it. The second column of the list of anomalies of the previous chapter shows strong positive Bouguer anomalies of several hundreds of milligal for all the deep sea stations while the columns of the isostatic anomalies show only slight values. This gives perhaps the most convincing evidence of the presence of compensating masses that has yet been published.

Once admitting that everywhere a tendency towards floating equilibrium of the crust prevails, it may be asked whether this tendency is the only force that is acting of whether there is evidence of other effects that might cause deviations from isostasy. The answer to this question is in the affirmative; it appears to the writer that there can be no doubt about the presence of such deviations. In the actual stage of the investigations, these deviations are more important than the confirmations of isostasy, because they may lead to the discovery of other phenomena. So we shall concentrate more particularly on the study of the deviations, i.e. the isostatic anomalies.

The gravity results at sea are important in this regard because they show some systematic characteristics, of which two especially deserve attention. In the first place the isostatic anomalies seem to show a tendency towards positive values in the shape of extensive fields of gravity excesses. Instances of this have been found in the Atlantic and in the Pacific and also in the deep basins of the West Indies. Only one instance occurs, between Socotra and Colombo, of a series of negative anomalies that might point towards a field of gravity defect, although it is still possible that it is no field of negative anomalies but a strip.

Negative anomalies have also been found at sea but more rarely and the writer gets the impression that they generally don't occur in fields but rather in belts. The clearest and most

remarkable instance has been found in the Netherlands East Indies in the shape of a narrow strip of excessive negative anomalies that will be discussed at greater length later on. Other evidences of the existence of such belts have, although in some cases less clearly, been found in the Atlantic over the Mid-Atlantic ridge, in the West Indies north of the islands of Porto Rico and Haiti and perhaps along the west-coast of Mexico and the United States and over the ridge of the Sandwich Islands.

The second characteristic is still more pronounced. Nearly everywhere the isostatic anomalies increase, in an algebraic sense, when going from shallow water to deep water. This has been found in a great many instances in the East Indies. It likewise occurs on the south-coast of Ceylon, near Socotra, at the end of the Channel where the deep sea begins and near the islands of Horta and São Miguel of the Azores. In the West Indies it was stated by the expeditions of the U. S. Navy at three places of a profile west of Cuba and Jamaica, in several places round the Gulf of Mexico, near the Virgin Islands and on the shelf between the Bahamas and the Atlantic. It was found by the expedition of Hr. Ms. K XIII to be the case on the west-coast of Mexico and the United States, and it was likewise found near the Sandwich Islands and near Strait Surigao in the Philippines.

This result was unexpected. For understanding it clearly, it must be realized that it has been obtained after the observations have been isostatically reduced. It cannot however be attributed to a wrong assumption of the distribution of the compensating masses, because it decidedly dominates the differences that can thus be brought about. This is proved by the fact that it shows up in the three series of isostatic anomalies given in the tables, i.e. in the Hayford-Bowie anomalies, in the Heiskanen anomalies and in the regional anomalies. We shall presently check this statement bij examining the gravity profiles more in detail.

The fact that the gravity results have been reduced isostatically, excludes that the above effect has anything to do with the coastal effect, computed by Helmert and other geodesists. This is caused by the attraction of the topography and the compensation of the coast; the isostatic reduction takes it away. The unexpected side of the question is that the sign is such that it means over-compensation of the coastal topography. Under-compensation, which could easier be understood, would give rise to the contrary effect, a decrease of anomalies, in an algebraic sense, when going from shallow depth to greater depth. The writer gets the impression that the effect is most conspicuous where the transition of the topography is steepest. The effect seems to occur as well near continental shelves as near oceanic islands. We shall come back to this remarkable effect in the ensuing paragraphs, in which we shall examine the gravity anomalies in the different regions that have been investigated, and likewise in chapter IX, where we shall try to find an explanation.

In the next paragraphs, we shall consecutively discuss the results in the Atlantic, the Pacific, the Indian Ocean, the Mediterranean and Red Sea, and in the Netherlands East Indies. A coloured world-map on a scale of 1:30.000.000 facilitates the study of the first four regions; it gives the position of the stations and their numbers corresponding to the list of the previous chapter. The oceanic and continental topography has been taken from the "Carte Bathymétrique des Océans", published by the Scientific Cabinet of the Prince of Monaco. It has not been corrected for the new sounding data that have been found during the expeditions.

Plate I gives a representation of the gravity results in these regions by means of profiles along the routes that have been followed. These profiles have the same horizontal scale as the map. 1: 30.000.000, save the detail profiles that are marked with Roman numerals and which

have been drawn on a three times larger scale, i.e. 1:10.000.000 in order to make them directly comparable to the East Indian profiles of Plate II, which are likewise on this scale.

The profiles show the topography and the isostatic anomalies according to the three adopted systems. As the Bouguer anomalies will only seldom be used for the interpretation, they are not represented in these profiles. The regional anomalies are indicated by the full line, the Hayford-Bowie anomalies by the dotted line and the Heiskanen anomalies by the dashed line. The vertical scales are the same for all the profiles of both plates. The depths are given on a scale of 1:1.000.000, that is to say they are thirty times exaggerated in the normal profiles of Plate I and ten times in the detailed profiles of that Plate and in all the profiles of Plate II. In all the profiles the depths are given according to the results of the soundings during the expeditions and so they may occasionally disagree with the world-map. The anomalies are represented on a scale of one mm to ten milligal. In most cases, continuous curves have been drawn through the indications of the anomalies for the different stations, in order to make these indications better readable, but of course no certainty can be given about the interpolated parts of these curves between the stations. In a few cases, where the interpolation would be too uncertain, the indications for the stations have been connected by straight lines.

The positions of the stations in the Netherlands East Indies may be found on the gravimetrical-geological map on a scale of 1:10.000.000, corresponding to the scale of the profiles of this area on Plate II. The transparent cover of the map gives the numbers of the stations, the isostatic anomalies according to the Hayford-Bowie method and according to the Heiskanen method, and the position of the profiles of Plate II. The map itself gives the regional anomalies and a corresponding system of isogams indicated by red colours for the negative values and yellow colours for the positive anomalies. The map likewise provides the geological data for the islands corresponding to the geological discussion of the gravity results by Prof. Umbgrove in chapter VI.

The topography of the sea-bottom of the East Indian Archipelago is represented on the second map on a scale of 1:5.000.000. This is a joint publication with the "Snellius Expedition"; the eastern half has been drawn according to the numerous sounding data provided by this expedition. The Leader of this expedition, Mr. P. M. van Riel. kindly gave permission for its publication although the report of the expedition has not yet appeared.

### § 2. The Atlantic.

In 1926 a crossing of the Atlantic was made via the Islands of Fayal (Azores) and Gran Canaria to the Mona Passage west of the island of Porto Rico It is indicated on the world-map by the stations 43 to 70. The results between Gran Canaria and the Mona Passage are represented on the first profile of the Atlantic on Plate I. All the stations in the eastern and middle part of the ocean show positive anomalies. This is clearly demonstrated by this profile and by the mean value of the anomalies. The average of the stations Nos 43 to 63 and of one station in the same area of a previous voyage, viz No 34 near Cape Finisterra, is + 35 mgal for the Hayford-Bowie anomalies, + 27 mgal for the Heiskanen anomalies and + 33 mgal for the regional anomalies. The lowest values are found in Horta, in the stations 50, 51 and 52 to the north-west of the Canarian Islands, and in station 62 over the Mid-Atlantic ridge (see first profile); in these stations gravity is about normal. As Horta is likewise situated on the Mid-Atlantic ridge, it makes the impression that the ridge shows less gravity excess than the deeper parts of this region.

The expedition of 1932 has given the opportunity to make a more detailed investigation of this area and the results have entirely corroborated the above conclusions. The stations of this expedition are indicated on the world-map by the numbers 426 to 486. The results are given in the profiles 2 to 7 of Plate I; they contain also the results of previous expeditions situated in or near the same lines. The results are connected by curves for giving a clearer insight but the way of interpolation between the stations is of course more or less uncertain. In a few instances, where the distance is too large, the connection has been made by straight lines.

The same uncertainty is true for the representation of the sea-floor in these profiles. During the last expedition the soundings were usually extended over a distance of a few miles to both sides of the station and so a few irregularities found by these soundings could be represented in the profiles but the long connecting parts between the stations could not be given otherwise than by smooth curves, although the numerous irregularities, found near the stations, indicate that the sea-floor over great parts of this area has an irregular topography.

We have already mentioned that the results confirm the conclusions obtained by the earlier expeditions. Profiles 2 and 3 show that, on leaving the European shelf at the end of the Channel, gravity begins to show a negative deviation, which, in both profiles, is strongest over the edge of the shelf over shallow water. At the continental slope this anomaly disappears and changes over to a positive value over deep water. So here we find a strongly pronounced instance of the second rule of § 1 according to which the anomaly increases when passing from shallow water to deep water.

Nearly all the further stations of the expedition show positive anomalies. If we take the average of all the stations from No 428 till No 485, we find + 35 mgal for the Hayford-Bowie, + 30 mgal for the Heiskanen anomalies and + 22 mgal for the regional anomalies. The first two figures correspond remarkably well with the corresponding averages of the previous voyages as they were mentioned above. The last figure is decidedly lower and differs more from the average for the other methods of reduction than ought to be expected according to the rule of page 19. A nearer investigation will be needed before a complete explanation of this deviation can be given. A slight difference from the Hayford-Bowie anomalies might be explained by the smaller depth of compensation, which brings the positive compensation in the ocean in a higher position, but according to the formula 6 A of page 19 this ought not to exceed a few milligal. This may in fact explain the small difference between the figures for the Hayford-Bowie and the Heiskanen anomalies, for the depth of compensation for the Heiskanen reduction is likewise smaller in the ocean than that of the Hayford-Bowie reduction. The larger deviation for the regional anomalies is fairly systematic over the whole area, as is clearly shown by the profiles, but it seems slightly larger near the European shelf. Profile 3 parallel to the Portuguese coast, for instance, shows rather large differences for nearly all the stations. This profile, moreover, shows a smaller gravity excess for all the curves.

Leaving aside this as yet unexplained difference, the fact remains that the new results corroborate the presence of the extensive field of positive anomalies that was already found by the previous expeditions. Taking the average of the old and the new stations together, with the exception of the stations 470 to 486 of the profile near to the Portuguese coast, we find a value of + 36 mgal for the Hayford-Bowie anomalies, + 32 mgal for the Heiskanen anomalies and + 28 mgal for the regional anomalies.

The new results likewise confirm the decrease of the positive anomalies over the Mid-Atlantic ridge. Profile 2 shows it clearly for the stations 436, 437 (Punta Delgada) and 438,

and the same can be said for the profiles 4 and 5 which give the west-east crossings over the ridge to the north and to the south of the Azores. The smaller distance of the stations in comparizon with the old crossing of the ridge in profile 1, allows now to make a more detailed investigation of this feature.

In neither of the three profiles over the ridge, evidence has been found of a narrow belt of negative anomalies like the one found in the Netherlands East Indies. So, as far as this object was concerned, the result of the expedition was in the negative and we may state that the Mid-Atlantic ridge, though seismically active, cannot be considered as a tectonic phenomenon of the same intensity. This is in harmony with the fact that the earthquakes here are decidedly weaker than in the East Indies.

Nevertheless, profiles 4 and 5 show two features which might point to a similar phenomenon on a smaller scale. Each of the profiles shows a narrow decrease of the anomalies, viz in stations 453 and 445, over a line that looks as if it is the continuation of the western ridge of the Azores, represented by the islands Flores and Corvo, and they each show a second but weaker decrease in stations 455 and 443, which are on a line with the central ridge of the Azores, containing the islands of Graciosa, Terceira, São Jorge, Fayal, and Pico. As, however, the deviations are so much weaker than in the Indies, it is much less sure whether we are allowed to connect these two profiles by two belts extending over the intervening space. The deviations may also be local and independent of each other. Nevertheless, the similarity of the two profiles, each with its two decreases of the anomalies at about the same distance from each other, and their apparent coincidence with two of the three ridges of the Azores, seems to be in favour of the above interpretation. Only further investigations can settle this question.

Profile 2, representing a south-north crossing over the island of São Miguel in the eastern ridge of the Azores, has a different character. It shows a decrease of the positive anomalies over a broader zone than the island, which seems to indicate that the decrease is not directly connected with the island itself. In the regional anomalies, the island does not show up; the regional anomaly in Punta Delgada is + 14 mgal and it is + 18 and + 21 mgal for the neighbouring stations over deep water. So the fundamental assumptions of the regional reduction method seem to be nearer to the actual situation here than those of the other methods, and so we may conclude that gravity appears to indicate the islands as a volcanic load on an unbroken crust. The gravity results for this island are contradictory to the current opinion that volcanic islands in the oceans show a great gravity excess because of the heavy volcanic material of which they are built.

A consideration of the different gravity profiles clearly shows the great irregularity of the gravity field in this whole part of the Atlantic; there are many more deviations in the profiles than those that have been considered above in relation to the Mid-Atlantic ridge. This irregularity is not surprising, considering the irregular topography of the sea-bottom, provided we consider this topography, at least partly, as the result of tectonic activity. Considering it in the light of the theory of Wegener as floating sialic remains of the zone of disrupture of the original continent, it would be less explicable. So gravity points in the same direction as the frequency of earthquake epicentra in the Atlantic; both facts render it probable that the Earth's crust in this part of the ocean is more or less rigid and capable to transmit stresses.

The distribution and the character of the irregularities of the gravity field are such that it does not seem possible to draw many conclusions. The deviations are not sufficiently strong or characteristic to allow to connect the results of the different profiles by interpolations through the intervening space. So a more detailed gravity research is needed before a good representation of the whole field will be obtainable. From the north-south profiles, Nos 1, 2, 6 and 7, we may only draw the negative conclusion that there is no more question in these profiles of a belt of strong negative anomalies than in those over the Mid-Atlantic ridge that have been examined above. Profile 3 along the Portuguese coast shows the strongest irregularities, but even here they cannot compare with the profiles in the East Indies. As no isostatic anomalies in the neighbouring parts of Portugal or Spain are available, it cannot yet be decided, whether these irregularities are continuations of similar features in the continent. The way in which they occur certainly suggests a relation to the tectonic features of the Iberian Peninsula. This is, of course, an interesting point as it may shed light on the problem whether the oceanic crust reacts in the same way on eventual stresses as the continental crust.

The island of Madeira (profile 5) shows fairly strong positive anomalies but here again the anomalies are not confined to the immediate neighbourhood of the island but they extend over some distance over the adjoining deep sea. So the excess is probably not related to the direct effect of heavy volcanic material and we may repeat the remark made about the gravity field near the island of São Miguel. The two gravity results in the stations 52 and 53 near the Canarian Islands are strongly different and so it does not seem possible to draw conclusions about these islands; the field appears to be disturbed here.

We shall now consider the western portion of the Atlantic, for which only the first profile is available. Knowing the great irregularity of the gravity field in the eastern part of the ocean, we have reason to suspect this profile of being too schematic and so we have to be careful in drawing conclusions. From the above profile it seems as if the positive field disappears west of station 63, but more evidence is needed before a final opinion can be formed.

A more detailed profile was observed over the Nares Deep north of the island of Porto Rico and, besides, many gravity values are available here of the expedition of the U.S. Submarine S—21, organized in 1928 by the U.S. Navy in cooperation with the Carnegie Institution of Washington. On Plate I a detailed profile of the gravity field over this deep is given, which has been derived from these combined data. It has been projected at about right angles to the axis of the deep and of the neighbouring island ridge. For giving a better understanding, a second profile A II has been added, which gives another crossing of the same tectonic axis via Windward Passage, between Haiti and Cuba. This profile was compiled from the data of a second American gravity expedition towards the West Indies, the expedition of the U.S.S. S—48, which was organized in 1932 by the U.S. Navy in cooperation with Professor Dr. Richard M. Field of Princeton University. Both profiles have the same vertical scale as the oceanic profiles, but their horizontal scale is three times enlarged, i.e. 1:10.000.000.

Profile A 1 shows a strong decrease of the anomalies over a rather narrow belt, — 183 mgal for the Hayford-Bowie anomalies, — 247 mgal for the Heiskanen anomalies and — 171 mgal for the regional anomalies. It might be expected that this would be an effect of the great defect of mass of the deep, because it would not be surprising that such a recent tectonic feature would not be entirely compensated. The axis of the belt of negative anomalies does not however exactly coincide with the deep; it is shifted towards the island ridge and so we get the impression that the explanation must be more complicated. This impression is corroborated by

the results of the two American expeditions and by the supplementing observations of the Coast and Geodetic Survey over the islands: They show that the belt of strong negative anomalies continues towards the west although the deep does not continue in this direction and so a direct connection with the deep is out of the question. Further westwards, south of Turks Islands, the character of the gravity profile begins to change. Profile A II gives an example of the new shape in this area. The negative belt here is broader and it is no longer symmetrical while the anomalies are not as strong as in the former profile. Here again we find the same independency of the surface topography. Still further westwards, south of E. Cuba, the negative deviation of the anomalies gets weaker and the feature disappears. We shall not further enlarge here on this remarkable feature which we shall discuss again in chapter IX. We shall find an analogous feature in the East Indian Archipelago, where the gravity data are more numerous and where, in consequence of this, a more complete discussion is possible.

### § 3. The Pacific.

Along the coast of Central and North America, between Panama and San Francisco, a series of twelve observations has been made at some distance from the coast over deep water. The numbers of the stations, beginning with No 78 and ending with No 99, may be found on the world-map and on the first gravity profile of the Pacific on Plate I. This profile clearly shows an excess of gravity along this route. The mean of the twelve Hayford-Bowie anomalies is  $\pm$  43 mgal, of the Heiskanen anomalies  $\pm$  28 mgal and of the regional anomalies  $\pm$  42 mgal.

At four places, viz at the stations Nos 81, 85, 90 and 99, profiles have been observed at about right angles to the coast. The results are given in the profiles P I, P II, P III and P IV of Plate I. Their horizontal scale is thrice that of the map and of the main profile, but their vertical scale is the same. All the profiles show the same character, a strong drop of the gravity anomaly, taken algebraically, near the shelf. This confirms the general characteristic mentioned in the beginning of this chapter, an increase of the anomalies when proceeding from shallow water towards deep water. It is obviously strongly pronounced along this coast.

When we take the mean for the four stations where the anomaly is lowest in each profile, Nos 84, 86, 92 and 98, we find — 32 mgal for the Hayford-Bowie anomalies, — 34 mgal for the Heiskanen anomalies and — 32 mgal for the regional anomalies. This means a drop from the ocean values towards these lowest values of 75, 62, or 74 mgal according to the system of isostatic reduction that is adopted. For profiles I and III we don't know the lowest value of the anomaly as it may still decrease further landwards, and so the value of this difference may here be under-estimated.

Examining the four profiles, it is worth noticing that the decrease of the gravity anomalies towards the shelf does not seem to coincide exactly with the change of the depth. In profiles I and IV this appears to be the case, but in profile II the lowest value is halfway the slope and in profile III the value over the foot of the slope is already remarkably low. This seems to indicate that the changes of the depth and of the gravity anomaly are not directly connected, but that their relation has an indirect character. An analogous result was already found in the Atlantic at the end of the Channel and near the Azores.

Another indication in the same direction is given by the profiles II and IV, which continue further landwards than the other profiles. They show that the anomalies tend to increase again nearer to the coast and this seems to indicate that the decrease that has been discussed has no direct relation to the continental shelf but that it is the outer half of a profile over a strip of low anomalies, which looks as if it is of a similar kind as the strip of negative anomalies in the Netherlands East Indies, which will be discussed afterwards. An indirect connection of the strip with the continental shelf cannot of course be denied as the whole feature is clearly parallel to the coast. Profiles II and IV show the strip to have a breadth of 60—80 km.

Comparing the Heiskanen anomalies to the regional anomalies, we see that the first curve shows a more gradual slope from the ocean towards the strip than the second curve and likewise a smaller difference of the anomalies. This is simple to explain. It is caused by the fact that the regional reduction method assumes a gradual change from the positive compensation masses under the ocean to the slight negative compensation in the continent, while the Heiskanen method assumes an abrupt transition. We can easily derive that this has the above effect. In this case of a continental shelf, there seems every reason to think that the latter conception will probably be nearer to the truth, and so probably the curve of the Heiskanen anomalies is to be preferred.

The crossing of the Pacific from San Francisco via Honolulu, Guam, and Yap to Strait Surigao to the north of Mindanao, is represented by the lower Pacific profile. We may notice that, as far as the general aspect is concerned, the three anomaly-curves give about the same results. They all show that the positive values to the west of the American coast don't continue over a great distance. From station No 100 till station No 104, which is situated about halfway to Honolulu, the anomalies are remarkably small. The bottom of the ocean is well-known here. because a dense strip of soundings stretches from San Francisco to Honolulu. Apart from one curious elevation near No 102, it shows no great irregularities.

From station No 105 till station No 125 there seems a general tendency towards positive values of the anomalies, which reminds one of the positive field found over the Atlantic. We find the following mean values for these stations: + 14 mgal for the Hayford-Bowie anomalies, + 14 mgal for the Heiskanen anomalies and + 16 mgal for the regional anomalies. The small differences of these values confirm the opinion expressed on page 19 of the first chapter, that the mean anomaly over a great field cannot vary much by changing over from one method of reduction to another method. Of course the assertion about a positive field over the central part of the Pacific is not as well founded as that about the Atlantic, because only one crossing has been made and the stations are situated at a mutual distance of several hundreds of kilometers. So we don't know anything about the extension of these anomalies at right angles to the route of the ship. The gravity excess is, moreover, less than in the Atlantic.

West of station No 125 we find an area for which the mean of the anomalies is about zero again; the mean of the stations Nos 126—130 is + 6 mgal for the Hayford-Bowie anomalies, — 2 mgal for the Heiskanen anomalies and + 2 mgal for the regional anomalies.

Between Honolulu and Guam, the sea-bottom is no longer as regular as east of Honolulu. The soundings at the stations 117, 118, 119, 120 and 122 revealed the existence of much smaller depths than the charts show. A comparizon of the world-map, which has been compiled from the old data, and the profile in which the soundings during the expedition have been taken into account, clearly shows the disparity.

Between the Marianas and the Philippines all the stations show again rather big positive anomalies which don't vary much. The mean of the Hayford-Bowie anomalies of the stations 139, 141, 142, 143 and 144 is + 62 mgal, that of the Heiskanen anomalies + 47 mgal

and that of the regional anomalies + 50 mgal. The sea-bottom seems to be more regular here as far as the few soundings of the expedition and the old data allow to conclude.

The crossings of the rows of islands, the Sandwich Islands and the Marianas, as well as the values near the Philippines, deserve especial attention. The gravity results have been represented in four profiles, P V, P VI, P VII and No 1 of Plate II. As well as it could be done they have been drawn at right angles to the island rows and where the gravity stations were not exactly on the line of the profile, they have been projected on it. The horizontal scale is the same as for the other detail profiles, i.e. three times that of the big profile over the Pacific.

Profile P V crosses the Sandwich Islands south of the island of Oahu (Honolulu). To the north-east the islands are bordered by a broad trough which is not deep; the greatest depth in this profile is only 5528 meters, while the slightly elevated ridge to the north-east of the trough shows a depth of about 4400 meters. The gravity-profile shows remarkable differences between the three curves of anomalies. While the curve of the Heiskanen anomalies has deviations of — 50 mgal over the trough and + 75 mgal over the island-ridge, the curve of the regional anomalies only shows — 13 mgal over the trough and + 37 mgal over the ridge, i.e. its fluctuations are less than half of those of the first curve. In fact these fluctuations are remarkably small for an area where the topography shows great irregularities. Another assumption for the data of the regional reduction may perhaps even further reduce them.

We may conclude that the assumptions on which this regional reduction is founded are in good agreement with the gravity anomalies and so it appears as if gravity can be explained for a large part by assuming that the islands are loads on an unbroken Earth's crust. This reminds us of the result found for the island of São Miguel (Azores). It seems to be in harmony with the hypothesis that these islands are entirely or for the greatest part formed by volcanic eruptions. The trough might then be explained as the down-warping of the crust under this load, although it must be recognized that in this case another trough ought to be expected on the south-west side of the island-ridge and nothing is found there. In any case, we may state that gravity does not point towards great disrupture of the crust or to strong disturbances of the normal distribution of the crustal material. This agrees with the absence of earthquake-centres in this area. Our conclusions are based, however, on a few stations only and further evidence will certainly be needed before a final opinion is possible. It will be worth while to study the results found by the U. S. Coast and Geodetic Survey in five stations on the islands, i.e. two on Hawaii, one on East Island, one on Nihoa and one on Necker.

Profile VI, over the island of Guam, is situated on the contrary in an area that is decidedly seismic and the deep trough to the south-east of this island likewise points to heavy tectonic activity. Gravity is in good agreement with these facts; all the anomaly-curves show strong deviations. We find here evidence again of a strip of negative anomalies, which is stronger pronounced for the Heiskanen anomalies than for the regional ones, but in the latter case it is also clearly visible. This strip seems to coincide with the trough. We shall come back to this question at greater length in the next chapter, where we shall try to find an explanation for the similar results in the East Indies.

The regional and Hayford-Bowie anomalies of this profile show a second downward curve, less pronounced than the first, over the island-ridge while the Heiskanen anomalies seem to be undisturbed here. So, this result is the reverse of what we have found over the Sandwich Islands, where the regional anomaly-curve was only slightly disturbed and the Heiskanen curve showed strong deviations. We get the impression that, in this case, the assumptions on

which the Heiskanen method is founded, correspond better to the actual state of things and that, accordingly, the island-ridge is supported by a local root of crustal material at the lower boundary of the crust. This points to strong deformations of the crust by lateral compression at the time this root came into being.

Profile VII, over the island of Yap, shows a similar result to the previous profile. This island, moreover, seems to belong to the same tectonic axis as Guam and so similar conditions may be expected here. There is a trough again to the east of the island, but the trough is less broad and deep than that of Guam. The three anomaly-curves likewise show a pronounced drop over the trough but the strip is narrower, which seems to agree with the smaller breadth of the trough. There is no evidence in this case of a second drop of the regional anomalies over the island although it is not impossible that it exists in some measure; a station to the west of the island at a small distance could give information, but as no observation has been made there, no opinion can be formed. So we cannot draw the same conclusion about Yap as about Guam.

The last profile, representing the crossing of the Mindanao Deep to the east of the Philippines, is given on Plate II, No 1. The trough is the deepest that is known on Earth. In the profile, the greatest depth is 9700 meters and a little to the north, the "Emden" and the "Snellius" have even found depths of more than 10.000 meters. The submarine slope to the west of the trough is exceptionally steep.

The gravity results of this profile are interesting. For the Heiskanen anomalies they show strong deviations of -58 mgal over the trough and +140 mgal over small depth in Strait Surigao to the west of the trough but the curve of the regional anomalies is remarkably regular. The regional anomaly over the trough has a value of +54 mgal, which does not appreciably differ from that of the preceding station, No 144, and so we see that this great topographic feature does not show up in these anomalies. We get to the conclusion that gravity is here in harmony with the assumption of the regional method of reduction, an unbroken Earth's crust, at least for the eastern half of this profile, i.e. for the trough and the neighbouring part of the ocean.

For the western part, the transition to the Philippine ridge, the regional anomalies show an increase, although considerably less than the Heiskanen anomalies; it is only 57 mgal instead of 198 mgal for the latter. This increase of the anomalies is an exception to the general rule that the anomaly increases when getting from shallow water to deep water.

We shall come back to the last three profiles in the next chapter.

### § 4. The Indian Ocean.

As the world-map shows, only one profile was observed in the Indian Ocean, which is represented on Plate I. It stretches from the island of Socotra near Africa via Minikoi, the most northern island of the Maladives, and via Colombo towards Sabang near the north-western extremity of Sumatra. From Colombo (No 24) till station No 26, the profile has a southerly direction.

Most of the stations are far apart and so the curves of the anomalies are correspondingly uncertain. They have been drawn for making it easier to get an impression about the results, but the interpolation between the stations cannot be relied on.

Near Socotra and south of Ceylon we find the coastal effect that has been mentioned in the beginning of this chapter: an increase of the anomalies when proceeding from shallow

depth to great depth. The pair of stations south of Ceylon, Nos 25 and 26, are only eighteen sea-miles apart and yet the anomalies show differences of 33 mgal for the Hayford-Bowie anomalies, 23 mgal for the Heiskanen anomalies and 59 mgal for the regional anomalies. The greater value of this difference for the latter anomalies may be well understood as it is obviously probable that the compensation of the continental and oceanic parts of the Earth's crust is more or less independent from each other and so the compensation near a steep shelf will rather have a local than a regional character. For the pair of stations near Socotra, Nos 17 and 18, the differences are in the same order 58, 43 and 64 mgal.

Other evidence, though less convincing, of the above coastal effect may perhaps be found near Minikoi and near station No 23 south of the Peninsula; they show stronger negative anomalies than the neighbouring stations over deeper water. Further investigation will be needed before we can make sure about it.

Near Sabang, the profile shows details that have not been derived from the stations of this profile but from a series of stations in the neighbourhood, which will be mentioned with the results for the East Indies.

The two most westerly stations of the profile over deep water, Nos 18 and 19, show about normal gravity. More to the east, however, we meet with two negative values, Nos 20 and 21, and the three stations over deep sea between Ceylon and Sumatra. Nos 26, 27 and 28, show likewise slight negative anomalies. The mean of the results for these five ocean-stations is — 20 mgal for the Hayford-Bowie anomalies, — 27 mgal for the Heiskanen anomalies and — 18 mgal for the regional anomalies. These negative ocean-values are an exception to the results found elsewhere in the oceans which, as a rule, show positive or normal values. The strongest negative anomalies of this profile are found near Minikoi and south of the Peninsula but these values cannot be considered as pure oceanic results. In these stations, Nos 22 and 23, the Hayford-Bowie anomalies are — 60 and — 96 mgal, the Heiskanen anomalies — 57 and — 66 mgal and the regional anomalies — 61 and — 84 mgal. For interpreting the meaning of these strong negative anomalies, they will have to be studied in connection with the gravity field in British India. The same may be said concerning the above oceanic results; it is unlikely that it will be possible to interpret them successfully without making a more intensive survey of this part of the Indian Ocean.

### § 5. Mediterranean and Red Sea.

We shall not go into details about the results in the Mediterranean because it cannot be expected that an independent interpretation will be possible of a small number of results in this extensive area with such an extremely complicated tectonic history. When the results of the Italian and French expeditions in the western part of the Mediterranean will be published, an interpretation of the results may be attempted with a better chance of success. So the writer wishes here to make only a few remarks.

The results are represented in the profile of Plate I. The five stations in the western part show strong positive anomalies. Their mean is + 64 mgal for the Hayford-Bowie anomalies, + 54 mgal for the Heiskanen anomalies and + 68 mgal for the regional anomalies. The stations in the eastern part show smaller anomalies.

It is interesting to see that the two values found to the north-west of the Nile-delta and the value obtained in Alexandria are all negative, i.e. — 23, — 20 and — 13 mgal for

the Hayford-Bowie anomaly, — 34, — 21 and — 13 mgal for the Heiskanen anomaly and — 27, — 27 and — 19 mgal for the regional anomaly. The first of these stations is situated over deep water, the second over a depth of 620 meters and the third is in the harbour of Alexandria. These values of the anomalies certainly give no indication of an appreciable lag in the readjustment of isostatic equilibrium during the deposition of the Nile sediments.

The whole series of stations in the Red Sea, i.e. Nos 12—15, and likewise the stations at Suez and Aden, show fairly strong positive anomalies. The mean for the four Red Sea stations is + 57 mgal for the Hayford-Bowie anomalies, + 50 mgal for the Heiskanen anomalies and + 56 mgal for the regional anomalies; in the same order the results for Suez are + 24, + 27 and + 29 mgal and for Aden + 39, + 36 and + 39 mgal.

## § 6. The East Indies.

In this area a great number of observations has been made; together 281 stations have been observed. They are represented on the 1:10.000.000 map of this publication. It is to be regretted that land observations have not yet been made in this area and so the only available data for the islands are those that have been observed with the K XIII in the harbours. This is more serious for the western half of the archipelago with its large islands, than for the eastern half, where the islands are smaller. It may be hoped that in the future this shortcoming may be remedied; the scientific importance of the area, which is, tectonically speaking, one of the most interesting on Earth, certainly warrants the continuation of the research on the islands.

The great number of the observations allows a much better insight in the character of the gravity field than for any of the previously examined regions. This leads likewise to a better possibility of interpretation and so, in the next chapter, the writer will begin his attemps by the East Indies. Another reason for doing so is the fact that the geology and the submarine topography of the archipelago is well-known and that it is also well investigated seismologically.

Before examining the gravity field in detail, a few general remarks may be made. For investigating the general equilibrium conditions of the Earth's crust in this region, the mean of all the anomalies has been taken and the following results have been obtained: +19 mgal for the Hayford-Bowie anomalies, +17 mgal for the Heiskanen anomalies and +20 mgal for the regional anomalies. The good agreement of these figures confirms the rule that the mean anomaly of an extensive area is independent of the method of isostatic reduction. As the archipelago has a very irregular topography, we may expect that locally the reductions according to different methods will differ considerably and the list of anomalies shows this clearly to be the case, but the mean of the three sets is practically the same.

The gravity excess of about 20 mgal in this great area, extending over 4500 km in easterly direction and over 2000 km in northerly sense, is remarkable. The great number of stations on which it is based and the agreement of the figures for the different methods of reduction makes it unlikely that we have to do with an apparent result that will disappear when more observations will be available. So we cannot escape from the conclusion that the Earth's upper layers are not in equilibrium in this region. The area is, moreover, situated in such a way, that the longitude term of the gravity assumed by several authors, would give a negative deviation instead of a positive one, and so this line of explanation, which might perhaps be attempted for the Atlantic and Pacific fields of excess, is out of the question here.

At a first glance we see already that locally the anomalies are showing great deviations. This is also clearly shown by the great values that are found when we take the mean of all the positive anomalies and of all the negative anomalies. For the Hayford-Bowie anomalies we obtain in this way mean values of + 44 and - 51 mgal, for the Heiskanen anomalies + 41 and - 49 mgal and for the regional anomalies + 44 and - 57 mgal. These large mean values are a striking indication of the great frequency of strong anomalies in this area. This is likewise shown by the enormous maximum and minimum values of the anomalies; they are found near to each other, between Celebes and Halmaheira, at the stations Nos 151 and 279, where at a distance of 180 km anomalies have been obtained of + 166 and - 204 mgal for the Hayford-Bowie reduction, of + 163 and - 210 mgal for the Heiskanen reduction and of + 142 and - 205 mgal for the regional reduction.

A nearer contemplation of the gravity anomalies reveals the existence of a great feature dominating the whole field, a narrow belt of strong negative anomalies, running through the archipelago, and bordered on both sides by fields of positive anomalies. This strip of a breadth of only some hundred kilometers is clearly visible on the gravimetric map which gives a coloured representation of the regional anomalies. The red colours show the strip of negative anomalies. It runs over the islands west of Sumatra, over the ridge south of Java, over the islands of Timor, Tanimber, Kei and Ceram, turns to the north between Halmaheira and Celebes and continues over the Talaud Islands towards the Mindanao Trough. It has a strong embranchment towards East Celebes, which probably continues over the south-east peninsula of that island, and a slighter and shorter one from Ceram towards Boeroe. <sup>1</sup>) Near the islands of Obi and Soemba, it shows weaker parts interrupting the course of the contours of the negative anomalies.

A clear representation of the strip is given by twenty-one profiles on Plate II, which have been drawn along the lines where observations have been made and as much as possible at right angles to the belt. Their positions have been marked on the transparent cover of the map, save No 1 which is outside it; it is a profile over the Mindanao Trough near Strait Surigao. Where a station did not coincide with the profile on which it is represented, it has been projected on it. In one instance, in profile 4, two stations to different sides of the profile, Nos 281 and 282, have been combined in one by taking the mean of the positions and of the anomalies. The horizontal scale of the profiles is the same as that of the map, i.e. 1: 10.000.000.

The profiles don't contain the Bouguer anomalies because these curves, which had originally been drawn, did not prove to be helpful for understanding the anomalies. They clearly show the drop of the anomalies over the belt, but the curves are so much complicated by the effects of compensating masses in the neighbourhood, that the common character of the curves gets lost. So they have been taken out for making the figures clearer but an instance is given

<sup>1)</sup> In this publication as well as on its maps, the names in the Dutch East Indies have been written in the Dutch way. The vowels are pronounced:

a as in far or in want,

e as a in made or as e in less or vowel,

i as ee in wheel or as i in, winter,

o as in English,

u as the German ü or as u in luck,

ij as i in like,

oe as u in include,

au as ow in how.

The g is sharp, more or less like the spanish j. The j is pronounced like the y in layer.

in profile 2. The three curves that are given in the profiles of Plate II represent as usual the regional anomalies by a full-drawn line, the Hayford-Bowie anomalies by a dotted line and the Heiskanen anomalies by a dashed line.

All the profiles show the same feature, a strong subsidence of the three anomaly-curves over the belt and positive values to both sides. The gradient of the anomalies is steep to both sides of the belt; in many cases it is even astonishingly so. One of the strongest examples is given by profile 4, where the gradient may be estimated at about 40 E ( $E=10^{-9}$  gal/cm), but in profiles 2, 15 and 16 it is certainly not much less.

The profiles clearly show that the negative anomalies are not brought about by a wrong assumption about the distribution of the compensating masses. The three anomaly-curves are so similar that we need not doubt that the differences which different methods of reduction may cause, are far inferior to the principal feature. This is likewise demonstrated by the Bouguer anomalies. They show that the strip of negative anomalies is already there before applying any compensation at all. An instance of this is found in profile 2. It is worth while noticing that even in this disturbed area, we can find a proof of isostasy; the fact that the Bouguer curves are so much more irregular than the isostatic anomaly-curves is a striking confirmation.

The profiles, as well as the bathymetric map, which contains a representation of the topography of the sea-bottom, show that the belt of negative anomalies is generally coinciding with a row of islands or a submarine ridge. This is rather unexpected, because it precludes the idea that the gravity defect could be caused by an uncompensated topographic mass-defect. The situation of the belt is strongly against this supposition because it is nearly everywhere beside the deep troughs that occur in the archipelago. Clear evidence of this is found south of Java, where the strip is beside the Java Trough, as profiles 13, 14, 15, 16 and 17 show. It is further demonstrated by profile 2, where the belt is over the Talaud Islands, while to the east of it the continuation of the Mindanao Trough shows depths of more than 8000 meters. It is clearly visible too in the profiles 7, 8 and 9, where the strip is shown beside the great depths of the Weber Deep. In short we may say that the same result is practically given by all the profiles, save by No 1 over the Mindanao Deep near Strait Surigao, where the character of the gravity defect, moreover, is different from that in the other profiles. This result does not exclude some other relation between the belt of anomalies and the troughs. Such a relation is indeed indubitable, because the features are everywhere parallel to each other and close together. An explanation of the belt will, therefore, have to account for this relation.

Examining the profiles, we see that in the whole middle part of the belt the profiles, from No 2 till No 17, are more or less symmetrical, but this is not the case for the profiles at the ends, i.e. profile 1 over the Mindanao Trough and profiles 18—21 west of Sumatra. These last profiles are clearly asymmetrical and at the same time the strip is broader and the anomalies in the axis are decidedly smaller than in the other profiles, as the following figures show. The average of the greatest negative anomalies of all the profiles from No 2 till No 17 is —114 mgal for the Hayford-Bowie anomalies, —115 mgal for the Heiskanen anomalies and —122 mgal for the regional anomalies, while the average for the profiles from No 18 till No 21 is only resp. —56 mgal, —48 mgal and —53 mgal and profile No 1 shows for its lowest anomaly values as high as +21 mgal, —58 mgal and +54 mgal. The transition from the narrow symmetrical type of profile with strong negative anomalies towards the broader asymmetrical type is not gradual but sudden. Profiles 2 and 16 show decidedly the first type and profiles 1 and 18 the second.

It is interesting to see that in the profiles 18—21 the regional anomalies show curves that somewhat better agree with each other than the Hayford-Bowie anomalies or the Heiskanen anomalies. So there is occasion to use the regional anomalies in the first place for trying to find an interpretation. We have already seen, when discussing profile No 1 in the previous § 3, that the same is true for this profile.

The continuation of the strip of negative anomalies in the direction towards East Celebes is clearly pronounced; the profile over this part (No 4) shows strong anomalies. The question may, however, be asked whether it is right to draw also a continuation of the negative belt to the south-east, in the direction of Ceram. It seems to the writer that this question ought to be answered in the affirmative; profile 5 between Laboeha and the Soela Islands shows clear evidence of the presence of such a continuation.

The continuation of the embranchment over East Celebes and from there over the south-eastern arm of this island, is problematical because no observations have been made on the island. The projected course of the contours is supported by the values found at the stations 308, 309 (Kolaka), 312 (Boeton), 314 and other stations near Celebes, but a good confirmation can only be obtained by a continuation of the research on land. A second motive for drawing the contours in this way, is given by the geological evidence which will be discussed in the following chapters.

Two remarkable relations of the negative belt to other phenomena may here be mentioned. In the first place, there is a clear relation to seismological data. The map published in 1930 by Dr. S. W. Visser of the Meteorological Observatory and reproduced on page 148 shows the epicentra in the Netherlands East Indies for the period of 1909—1926. We see that they are nearly all situated over or near the belt. This obviously suggests, as it might already be expected beforehand, that there is a narrow connection of this feature with the tectonic phenomena in the archipelago. Still, another explanation is likewise possible. We might explain the relation also by assuming that there must be a tendency towards the readjustment of the great deviations from isostatic equilibrium and that this must bring about vertical movements of the Earth's crust which cause the earthquakes.

The latter explanation seems less efficient than the first one. The archipelago shows everywhere evidence of strong tectonic activity and so it appears indicated to attribute the earthquakes to this activity and not to secondary phenomena as readjustments of equilibrium disturbances that have been brought about by former tectonic activity. As many of the earthquakes belong to the strongest type that is known on Earth, is seems difficult to attribute them to such secondary movements. In general the writer's opinion is that it is more logical to assume the primary cause, the tectonic activity, to cause as well the disturbances of isostasy as the earthquakes.

In the second place there is a curious relation of the anomaly-belt to the distribution of the volcanoes. This distribution is represented in fig. 27 on page 149. We see that everywhere, where the axis of the belt is curved, volcanoes occur in a row, parallel to the belt, at a distance of a few hundred kilometers at the inside of the curve. We find this to be true for the row of volcanoes of the Sangir Islands (Siao), N.E. Celebes and the volcano of Oena Oena (to the S.E. of Gorontalo), for the row of volcanoes of Ternate and the neighbouring islands and for the row of the inner Banda arc, continuing from Banda over the lesser Sunda Islands, with the exception of an interruption to the north of East Timor which exactly coincides with the reversal of the curvature of the anomaly-belt at this spot. We shall come back to this remarkable feature in the next chapter.

The profiles over the Banda arc, Nos 6—10, show another feature besides the strip that deserves the attention. The curves of the regional anomalies all show a secundary decrease of the anomalies over the inner Banda arc, which is not strong enough to show up in the coloured map, but which is clearly visible in the profiles. In most of the profiles, this decrease is not found in the curve of the Heiskanen anomalies; only in profile No 6 over Banda, an effect is also to be seen in this curve. With the exception of this last profile, we have here the same thing as has been found in the profile over Guam in the Pacific; besides the main strip of negative anomalies, there is a second slighter one in the curve of the regional anomalies, which is not present in the curve of the Heiskanen anomalies. We arrive at the same conclusion as for the Guam profile that the Earth's crust has a local root below the inner Banda arc, which compensates the island-ridge above it. We have thus to assume that the crust has been compressed by lateral pressure. The profile over Banda gives the impression that here the root is larger than is necessary for compensating the ridge.

Profile No 8 shows, to the east of the great belt, a contrary feature. Between the Kei Islands and the Aroe Islands, there is a secondary depression in the sea-bottom and over this deep the Heiskanen anomalies show a decrease while the regional anomalies are nearly undisturbed. So it appears as if the Earth's crust has not been disrupted under this feature and that the deep has somehow got into existence as a defect of mass at the surface of the crust.

Profile 12 shows a widening of the strip of negative anomalies. More observations will here be necessary before a good insight can be obtained. The same is true regarding the area round Soemba, where apparently the strip is much weaker. For these abnormal regions in the archipelago, the distances of the stations have been too great for allowing a complete understanding.

In several areas anomalies have been found that are lower than the surrounding positive field. We may point out here a few instances for which the geological data provide us with an explanation and which have accordingly been indicated by a separate colour on the coloured map. They are found near the north-coast of Sumatra, in Strait Soenda between Sumatra and Java, in strait Madoera, near Balikpapan, and in the Celebes Sea near the coast of Borneo. We shall discuss them in the ensuing chapters.

Near the Asia Islands, another instance is found of an anomaly that is lower than the neighbouring values. Here again the data are insufficient to form an opinion, but it may be pointed out that these islands are situated in the prolongation of the tectonic axis that passes over the islands of Yap and Guam. We have seen in our discussion of the results in the Pacific, that the profiles over this axis near Guam and Yap show the existence of a strip of negative anomalies that seems similar to the strip in the East Indies, and it is an obvious suggestion that the lower anomaly near the Asia Islands might reveal the continuation of this strip towards these islands. The present material does not allow an idea about its eventual further course.

The fields of positive anomalies in the archipelago deserve a nearer examination. In this regard we may divide the whole area in two parts, a western part and an eastern part, in the same way as it is done by the geologists. Excluding the strip outside the islands of Sumatra and Java, the western part, extending up to the shelf east and south-east of Borneo, is a stable area. The part that is covered by water, i.e. the Java Sea, has a continental character with shallow depths up to about 50 meters. The anomalies over this part are all positive and don't

show great fluctuations. The mean value of 28 stations is + 24 mgal for the Hayford-Bowie anomalies, + 28 mgal for the Heiskanen anomalies and + 32 mgal for the regional anomalies.

The positive anomalies found outside the negative belt in the Indian Ocean show about the same values. The mean of thirteen stations at some distance from the belt gives values of + 33 mgal, resp. + 23 mgal and + 22 mgal. Quite near to the strip the value of the anomalies is somewhat higher; taking the highest positive anomaly of each profile from No 13 till No 21 at the ocean-side of the strip, we find mean values of + 65 mgal, resp. + 53 mgal and + 48 mgal. This gives differences with the mean negative anomaly in the axis of the strip, as we have found it above, of 179 mgal for the Hayford-Bowie anomalies, 168 mgal for the Heiskanen anomalies and 170 mgal for the regional anomalies.

The eastern part of the archipelago has an entirely different character. From a tectonic standpoint it is unstable and the submarine topography is extremely irregular. Its details will be discussed at length in chapter VIII by Dr. Kuenen, the geologist of the "Snellius expedition". This expedition, by its great number of soundings, contributed much to our knowledge of the topography. Among its many interesting features we shall here only mention the deep basins. According to the bathymetric map we find four outstanding among the others, the Celebes Sea, the N.W. Banda Sea, the S. Banda Sea and the Weber Deep. Of these basins, the last has the character of a trough and is no doubt connected with the belt of negative anomalies in the same way as e.g. the Java Trough. The other three basins have a different character; they are broader and have a relatively flat bottom.

The gravity anomalies show a remarkable relation to the last basins; the strongest positive fields roughly coincide with them. This is clearly shown by the comparizon of the yellow areas of the coloured map with the bathymetric curves of the other map. The correlation is such that no doubt can exist of their being causally related. The following figures may be given. The mean of the anomalies of six stations in the Celebes Sea is + 89 mgal for the Hayford-Bowie anomalies, +71 mgal for the Heiskanen anomalies and +78 mgal for the regional anomalies. The mean of three stations south of the Soela Islands is in the same order + 131 mgal, + 112 mgal and + 123 mgal, and the mean of five stations in the southern part of the Banda Sea is + 92 mgal, + 67 mgal and + 80 mgal. The positive field in this last area seems to continue in the Gulf of Boni between the two southern peninsulas of Celebes, but the connection is not quite certain.

It is worth noticing that the positive anomalies occur up to the edges of the basins. Striking evidence of this is found in the Celebes Sea and on the northern edge of the deep south of the Soela Islands. So at the borders of the basins there seems to be no gradual transition of the anomalies but a sudden one. It needs not be stressed that these transitions are further confirmations of the second rule expressed in the beginning of this chapter, the increase of the anomalies when proceeding from shallow depth towards great depth. A great number of such confirmations may be found in the archipelago. Not only do they occur at the borders of the above deep basins, but they do so too at many places in the profiles over the belt of negative anomalies; a clear instance is e.g. given by the transition of the negative anomalies of the belt south of Java towards the positive anomalies in the Indian Ocean: this transition coincides with the strong increase of the depth from the ridge towards the Java trough.

The correlation of deep basins with excesses of gravity has also been found in another tectonically active area, viz. in the West Indies; the gravity expeditions of the U.S. Navy have shown strong positive anomalies in the Gulf of Mexico and in the sea west of Cuba and here

also the transition from the positive values towards normal gravity on the borders of the basins has in several places been found to be a sudden one.

This correlation may be considered as an unexpected result. When expressing it in terms of isostasy, it means that the basins are strongly over-compensated. So, when we assume that there is a tendency towards the readjustment of the equilibrium, we should have to expect that they must still tend to become deeper.

The stations in the Pacific, to the north of New Guinea and to the east of Halmaheira show also a great gravity excess, with the exception of the station near the Asia Islands that has already been mentioned. Maximum values have been found at station No 257, where the Hayford-Bowie anomaly shows a value of + 133 mgal, the Heiskanen anomaly one of + 113 mgal and the regional anomaly one of + 143 mgal. We cannot of course decide how far this positive field continues in the ocean and so no further conclusions about its character can be drawn. It seems worth while to organize an investigation in this region, which at the same time might disclose whether there is a second belt of negative anomalies here continuing towards the Marianas.

We have already seen that the second of the rules mentioned in the beginning of this chapter is confirmed in many places in the East Indies. After our summary of the results it is barely necessary to point out that this area likewise bears out the first rule, which states that the negative anomalies rather occur in belts and the positive in fields. The East Indies indeed show much evidence in this direction.

## CHAPTER V.

# Interpretation of the Gravity Anomalies in the Netherlands East Indies.

## § 1. Introduction.

In the first chapter, p. 17, it has been proved that, in general, gravity anomalies cannot be caused by deviations of the geoid. On the contrary, when taking these deviations into account i.e. by reducing the observed gravity value from the geoid to the ellipsoid before comparing it to normal gravity, the anomaly must generally be larger than before. So, for explaining anomalies, we have to admit the existence of abnormal masses.

On p. 37 et seq of the same chapter we have seen that in this respect we have to choose from four possibilities. We may suppose these masses at the Earth's surface in the shape of topographical features that are not compensated isostatically, we may suppose them in the crust, we may suppose them at the lower boundary of the crust as roots of lighter crustal material displacing the denser substratum or, in the opposite case, as the substratum taking the place of crustal material, and lastly we may assume them in the substratum. We shall have to consider each case in the light of the data from other sources for choosing between those possibilities.

It would be a natural procedure to take first into consideration the two characteristic features of the anomalies at sea, that have been pointed out in the beginning of the previous chapter, i.e. the fact that it appears as if the negative anomalies usually occur in strips and the positive in fields, and the second fact that in many cases the anomalies increase, algebraically speaking, when going from shallow depth to great depth. This does not, however, seem advisable. These characteristics cannot at all be easily understood in the light of our actual knowledge of the phenomena of the Earth's crust and so we cannot hope to be able to find a general explanation before getting a deeper understanding of these problems. So it seems better to start with an examination of special fields and more definite problems that can be attacked from many different sides together. Afterwards, at the end of chapter IX, we shall come back to the general features.

Of the areas covered by this publication, the most appropriate for an interpretation is the East Indian Archipelago. The number of gravity stations is sufficiently large for getting a good insight in the general features of the gravity field and in the second place it is well investigated in other directions that are useful in this connection. The geology has been studied by many well-known geologists as Verbeek, Fennema, Martin, Molengraaff, Tobler, Wing Easton, Brouwer, Rutten, Musper, Zwierzycki and many others. The topography of the sea-bottom is better known here than in most similar areas; besides the older soundings, which gave already a good idea of its principal features, the numerous data are now available of the oceanographic expedition of the "Willebrord Snellius", which, in 1929—1930, under the leadership of Mr. Van

Riel, has made more than 33.000 echo-soundings in this area. Chapter VIII contains a detailed discussion of these results by Dr. Kuenen, the geologist of the expedition. The area has also well been studied by volcanologists; a map of the distribution of volcanoes is found on p. 149. Lastly it has been investigated seismologically as the map on p. 148 of the distribution of the epicentra in the archipelago during the years 1909—1926 shows; the study and the map are due to Dr. S. W. Visser of the Meteorological Observatory at Batavia.

An important point is further that Prof. Dr. J. H. F. Umbgrove, Professor of Geology at Delft, has been found willing to cooperate with the writer in trying to unravel the relation of the geology and the gravity anomalies. He has made a critical study of the geological data of the Tertiary that are known and even some that have not yet been published but which have been kindly communicated by the explorers. The gist of his study is given in the next chapter. Besides its importance from a purely geological standpoint, it is invaluable for the interpretation of the gravity anomalies and his results will be frequently made use of in this chapter.

## § 2. Interpretation of the belt of negative anomalies; Buckling Hypothesis.

We shall begin our discussions with the principal feature of the gravity field, the belt of strong negative anomalies, which runs through the whole archipelago and which is clearly visible on the coloured map and in the profiles of Plate II. We have seen in the preceding chapter that it generally coincides with island rows or submarine ridges and so this excludes its being caused by topographic mass-defects that are uncompensated; if that were the case, it ought to coincide with the troughs and not with the ridges beside them.

It appears also unlikely that it is caused by recent movements of the Earth's surface which, when brought about by tectonic forces, might have caused disturbances that are not yet compensated. This would mean that we should have to assume a sinking of the surface in the belt and this is in contradiction with the unmistakable evidence of rising that is found on many islands of the belt. In general it does not appear probable that the belt would be in a state of down-warping.

So it seems difficult to look for an explanation of the belt by assuming uncompensated surface features. This discards the first way of explanation. The fourth, which looks for the cause in phenomena and mass-irregularities in the substratum, does neither appear likely because the steep gradients of the anomalies from the negative values in the belt towards the positive values beside it, make it probable that the cause is situated near the Earth's surface. A depth of some fourty kilometers seems about the maximum that can be admitted.

So everything points to the second or third possibilities of explanation, i.e. disturbing masses in the crust or at its lower boundary. We cannot expect to find an explanation of it in a wrong assumption about the distribution of the isostatic compensation; the anomalies are too large and their distribution does not agree with it. The fact, which has already been discussed in the previous chapter, that the curves corresponding to the different methods of isostatic reduction all show the principal feature equally well, is a strong proof against it.

We get to the conclusion that we must admit the presence of a great amount of light mass in the upper layers of the Earth. When assuming a defect of density of 0.6, we find that a cross-section is needed of more than a thousand square kilometers. What can be the cause of

this surprising feature and where do we have to localize it? Only considerations from other sides can guide us in trying to find an answer to these questions.

We have already seen in the previous chapter, that there is undoubtedly a relation between the belt and the epicentra of the earthquakes and so we must assume that the mass-defect is narrowly related to the tectonic activity in the archipelago. Now all the geological evidence points towards great lateral compression in the Earth's crust in this area and this conclusion is likewise borne out by the submarine morphology of the archipelago as it is clearly demonstrated by Kuenen in chapter VIII. It is also in harmony with the results of the gravity research; the gravity field shows a positive mean anomaly of about +20 mgal and as the average is derived from a great number of stations, there seems to be no reason to doubt it. Now we have seen in the first chapter that there are two possible ways of explaining an excess of gravity over such an extensive area, lateral compression in the Earth's crust or descending currents in the substratum, and as this latter assumption likewise involves lateral compression of the crust, both explanations concur in corroborating the above result. The fact that descending currents in general must imply compression of the crust, is made clear by realizing that such a current must be fed by converging horizontal currents below the crust and these currents must exert a viscous drag on the crust which will lead to compression.

So the geological evidence, the morphological evidence and the gravimetrical evidence all lead to the same conclusion of lateral compression in the Earth's crust. It seems, therefore, indicated to suppose that the tectonic phenomenon in the archipelago is a giving way of the crust to this lateral compression. Supposing for a moment that the crust in the belt where it is thrust together, has no appreciable strength, we can easily foretell what will occur. The crust will form a bulge to both sides and as we have to assume that the phenomenon takes place under maintenance of the isostatic equilibrium, the downward bulge at the lower boundary of the crust will be about four or five times greater than that at the surface of the crust, i.e. in the same ratio as the superficial density of the crust is greater than the difference of densities of the crust and the substratum at the lower boundary of the crust. If the deformation took place in this way, there would be no isostatic anomalies because at any time the excess of mass, caused by the upward bulging, would be compensated by the defect of mass, brought about by the downward bulge where the lighter crustal material displaces the heavier subcrustal material. The strength, however, of the crust, which opposes the deformation, must modify this process and involve another way of deformation and so we need not be surprised if isostasy is not continuously maintained during its different phases.

In the light of this reasoning, the interpretation of the belt of negative anomalies is evident; it seems indicated to consider this belt as the deviation from isostasy attendant on the above phenomenon. It thus sheds important light on what occurs. The obvious conclusion is that a great downward protuberance is developing, which causes a great mass-defect corresponding to the strong negative anomalies, while the upward protuberance of the above scheme is developing much slower. It is not quite absent, because the belt is indeed coinciding with a ridge, but the ridge is by far insufficient to compensate by its attraction the defect of gravity corresponding to the root.

This hypothesis thus gives a natural explanation of the fact that the belt is usually coinciding with a ridge and not with a trough. It likewise explains that the phenomenon is accompanied by heavy earthquakes; knowing that the root must have a cross-section of more than a thousand square kilometers, we may realize the magnitude of the phenomenon. The formation

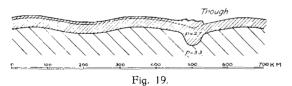
of this root must indeed be a considerably larger process than the developing of the surface folds and overthrusts that form the substance of our mountain-ranges.

The question may be considered why the downward bulge of the crust develops so much quicker than the upward bulge, although it might be thought that the substratum must exert a resistance, which is not met with by the upward protuberance. The resistance, however, of the substratum is probably viscous and so it must be small when the speed of the downward movement is small. Gravity, on the contrary, must favour the formation of the downward bulge, because this bulge has to be pushed downwards against a density difference of about 0.6, while an outward bulge, that has to be pushed upwards, has a density of about 2.7. For this question the writer may refer to p. 52 where this point has been examined and where also other reasons are given why a downward protuberance has more chance to come into existence than an upward one.

It is worth while to notice that the development of a great downward root and only a slight outward ridge indicates that the crust reacts more or less as a whole on the forces that try to deform it. If it would be totally crushed before bulging downwards, there seems to be no doubt that isostasy would be better maintained during the whole process than is apparently the case. Taking all the indications together and taking into account the theoretical results of § 8 of the first chapter, we come to the following supposition as to the general course of events.

In the beginning, when compressive stresses begin to develop, the crust must be expected to react in one of two possible ways. When it is perfectly homogeneous, it will undergo compression without appreciable vertical movements and without developing waves. When, however, it is layered, it is possible that waves will develop of a length of one or two hundred kilometers, which originally will be symmetrical with regard to the normal position of the crust, i.e. the outward waves have the same height above it as the downward ones are below it. When the downward waves get below sea-level, they become deeper. Gradually erosion and sedimentation will alter the phenomenon and the downward waves will tend to subside more and more. At a certain stage, the strength of the crust will be exceeded and disrupture sets in in the downward waves, which will buckle inwards. A root begins to develop.

The surface layer of the crust will no doubt undergo strong crushing in the central buckling zone and it can easily be understood that, at a certain stage of the phenomenon, it will begin to bulge outwards in irregular folds, which will cover the downward buckling of the main



crust-layer. Thus a ridge will develop. Incase this superficial layer is thinner or perhaps even lacking at one side of the ridge, we may expect that at that side the downward movement is not quite hidden and that a trough will reveal it. In the archipelago, many in-

stances of this are found; several troughs exist beside the buckling zone and always at the deep sea side of the zone. Striking examples are found south of Java, near the Tanimbar Islands and near the Talaud Islands (Profiles 2, 9, 14, 15 and 16 of Plate II).

When in a later stage of the phenomenon the compressive forces are again decreasing, the crust will get more liberty to resettle locally in isostatic equilibrium. The zone of strong negative anomalies must have a strong tendency to rise but in the present stage the lateral pressure in the crust is apparently too great to allow of such a readjustment independently of the neighbouring areas. It may, however, be expected that this will come to pass in a later stage

when the compression has diminished. So, on the long run, the rising of the ridge will probably reestablish the isostatic equilibrium and the whole structure will then have reached the last stage of the folded mountain-range, in equilibrium over its compensating root of crustal material at the lower boundary of the crust. Such a stage, for instance, is realized in the Alps and in other folded mountain ranges.

Before developing this hypothesis more in detail, we shall have to examine whether its general features are in harmony with the facts as they are known. We have seen that this is the case in the archipelago as far as the gravity, the morphology of the sea-bottom and the seismological data are concerned; for the morphology of the sea-bottom the writer may also refer to the study of this subject in chapter VIII by Kuenen, where K. comes to the conclusion that the troughs near to the belt must be connected with folding phenomena of the Earth's crust. But how stands the matter with regard to the principal body of facts, the geological evidence? Does this likewise agree with the above hypothesis?

Thanks to Umbgrove, this question can receive a definite answer and this answer is undoubtedly in favour of it. By his critical study of the geology since the beginning of the Tertiary, of which he gives a summary in the next chapter. Umbgrove found that no islands in the archipelago, save those in the belt, show great folding or overthrusting, while those in the belt that have been investigated — and this is the great majority — show clear evidence of it. So it can be considered to be proven that this belt has been subject to strong folding and overthrusting while no other part of the archipelago has undergone crustal shortening of a comparable amount during the Tertiary. The remarkable coincidence of the islands of strong folding with the belt of negative anomalies is clearly shown by the coloured map, where the blue colour of the folded areas everywhere occurs in the red strip of the negative anomalies. The strike of the folding, moreover, is generally parallel to the belt.

So the geology of the archipelago is in good agreement with the hypothesis that has just been outlined. We shall afterwards, in § 3, consider it from a more general standpoint to see whether it is likewise in harmony with the usually accepted views about the geological and geomorphological phenomena of mountain-formation in geosynclinal areas. First we shall consider more in detail the gravimetric evidence in the Archipelago which we shall now examine in the light of this hypothesis.

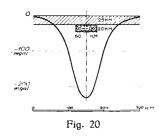
Admitting that the crust in the belt of negative anomalies has been subject to a lateral shortening through compression, which with regard to the above geological results seems a safe conclusion, we may draw two further conclusions from the way in which the belt is situated. The first conclusion is that we have obviously to do with a border effect of the Asiatic continent. It does not appear risky to express the view that it forms part, on one side, of the geosynclinal belt that continues from the Himalaya towards the south-east and, on the other side, of the belt of arcuate island ridges that borders the Asiatic continent on the east side; it seems to form the connection between those two geosynclinal belts. So the Himalayan geosyncline does not appear to continue towards New Guinea, as it has often been supposed, but towards Japan.

In the second place, it is worth while to remark that the anomalies are just as strong in the part of the belt that borders on the Indian ocean than in the part bordering on the Australian continent. This appears to indicate that the resistance offered by the ocean-floor of the Indian Ocean is not inferior to that offered by the Australian continent. It is not necessary to point out the importance of this conclusion for our general views about continents and oceans. It seems to

be in decided contradiction to Wegener's theory of continental drift; we could not well imagine such a migration through the ocean-floor when this part of the crust can so strongly resist pressure. Of course the actual facts only concern the floor of the Indian Ocean south of Sumatra and Java and the floor of the Pacific east of the Talaud Islands and so this conclusion ought not, without further proof, to be extrapolated to all ocean-floors elsewhere.

The consideration of the gravity profiles from No 2 till No 16 shows a remarkable symmetry over the belt. This points to a root that is symmetrical with regard to a vertical plane in the axis and this leads us to suppose that the crust, after buckling inwards, is thrust more or less vertically downwards. It certainly does not make the impression that one part of the crust is shoving under the second part, as we might perhaps expect to occur. On second consideration, however, this is not as surprising as it might appear at first. When a fold of the crust is pushed upwards, it must be expected to slide more or less horizontally over the crust, for in this case the density of 2.7 would make a vertical uprising difficult to understand. A downward root, however, differs much less in density from the subcrustal environment, and so a vertical downward movement seems admissible.

For one of the profiles, i.e. for No 16, the writer has tried to make an estimate about the dimensions of the root. For this purpose, the curve of the regional anomalies was chosen, because in this area of strong lateral compression local adjustments of isostatic equilibrium are improbable; in fact they don't occur, for else the belt of negative anomalies would readjust itself. So it may be expected that the regional anomalies are nearest to the actual situation. Assuming a density difference of 0.6 between the crustal and subcrustal material, it was found that a rectangular cross-section of  $20 \times 60 \, \mathrm{km}$  approximately corresponds to the curve of regional anomalies. The curve of attraction, brought about by this cross-section, is given by fig. 20 and it is likewise added in profile No 16 in order to allow the checking of the correspondence. This is of



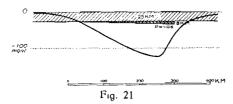
course no proof that the root has actually these dimensions, but the total area of the cross-section cannot differ much from the above amount and it cannot be much broader because in this case the attraction curve at the surface would be likewise broader. It is certainly possible that the mass-defect which causes the negative anomalies is not entirely concentrated at the lower boundary of the crust. When the crust would consist of more than one layer and when accordingly the density increase from the value of 2.7 at the surface of the crust to the value of 3.3 of the substratum

would be divided over more than one discontinuity surface, only part of it is concentrated in the root and part must be localized in the crust in smaller protuberances of each upper layer in the contiguous lower layer at each discontinuity surface. It does not appear possible to decide from gravity only whether this is the case. Such a modification, however, would not alter our considerations and so we may leave this question undecided.

From the cross-section of 1200 km<sup>2</sup> of the root we may conclude that the crustal shortening of a crust of a thickness of 25 km would be about 50 km because the product of both dimensions must correspond to this cross-section. This value for the crustal shortening cannot be considered as more than an indication of its order of magnitude, because the above value for the thickness of the crust is uncertain. Still it gives some idea about the movements that have actually taken place.

The four profiles west of Sumatra, Nos 18-21, show another type; they are clearly

asymmetrical, the strip of negative anomalies is broader and the anomalies are smaller. For the same reason as for the other profiles it seems advisable to use the regional anomalies; the crust is too much subject to lateral compression to expect that it can settle locally into equilibrium and the presence of the great anomalies proves that this presumption is right. So we may assume that the regional anomalies correspond better to the actual way of compensation and it is, therefore, not surprising that their curves show a somewhat better mutual correspondence in the different profiles. Looking at the character of the curves it seems indicated to try whether they can be explained by a shoving of one part of the crust over the other or, expressing it more accurately, a downward displacement along a shearing plane of one of the parts with regard to the other. This supposition proves to be successful; fig 21 gives the attraction curve of a corresponding distribution of masses and a comparizon with the profiles shows a good agreement.



Although this is no absolute proof that we have found the actual distribution of masses, the chances are good that our assumption is right. This would indicate that there is only a small component of the relative movement of the two crustal parts at right angles to the axis of the belt. This result, in connection with the general configuration of the course

of the belt through the archipelago, suggests the important conclusion that the compression is not acting in all directions in the crust but only in one which probably is best assumed to be about S.S.E. This direction makes only a slight angle with the direction of the belt west of Sumatra and so the movement in this area would indeed be chiefly a sliding of one part along the other with only a small component towards each other. A good confirmation of such a relative movement is provided by the crust movements accompanying the earthquakes in Sumatra which generally show the same character, a sliding along lines parallel to the axis of the island.

Near Strait Soenda the direction of the belt changes and the angle enclosed with the supposed direction of the force increases. The relative movement of the two crustal parts would thus get here a much stronger component at right angles to the belt, which means a greater shortening of the crust. This is in harmony with the altered character of the gravity profiles, which in profile No 16 suddenly assumes the symmetrical type corresponding to such a shortening.

The writer may call attention here to a circumstance that seems to be related to this transition of the type of crustal deformation near Strait Soenda. Some geologists, as e.g. Verbeek, van Es, Brouwer, Smit Sibinga, Schürmann, a.o. have expressed the views that Java seems to be shifted southwards with regard to Sumatra over a distance of some fourty kilometers. (See chapter VII, § 4). The supposition is based on the topography of the islands and of the sea-bottom to both sides of the strait. This fact would be in remarkable agreement with the difference of crustal shortening in the belt to the west and to the east of the strait and so it seems indicated to suppose that the greater shortening south of Java is caused by a relative southward movement of the crustal block that carries Java with regard to the block carrying Sumatra. A confirmation of such a relative movement appears to be given by the frequency of great earthquake-epicentra in Strait Soenda. The evidence, however, seems yet to be too vague to justify further elaboration of the hypothesis.

A parallel to the different data west of Sumatra and south of Java, which have lead to

the supposition of a direction of the crustal movement towards the S.S.E., is found in the data east of the Philippines and east of the Talaud Islands. When we again base our considerations on the regional anomalies, profile No 1, east of the Philippines over the Mindanao Trough, shows no evidence at all of crustal shortening. There is of course a difference between the anomalies in the eastern part and those in the western part of the profile, but this does not point to a root at the lower boundary of the crust that could be interpreted as a proof of a thrusting together of the crust in the way other profiles over the belt indicate it. So, incase we assume, in connection with our general theory, that the crustal block west of the trough moves with regard to the block east of it, we have to suppose the relative movement to be parallel to the trough. This is in good agreement with our supposition regarding the general direction of the movement.

Profile No 2 over the Talaud Islands shows, on the contrary, strong evidence of crustal shortening. It has the symmetrical type, which corresponds to the buckling interpretation and the negative and positive anomalies are especially large,—149 and +117 mgal; the root must, therefore, have a still greater cross-section than has been computed for profile No 16 and the shortening of the crust must be correspondingly larger. The sudden transition of the crustal deformation between both profiles coincides again with the change of direction of the belt, which near the Talaud Islands must give rise to a considerable component of the crustal compression at right angles to the axis of the belt. So here also the increase of the compression between the two profiles may be explained by the supposition about the S.S.E. direction of the compressional force.

A parallel to the data which have lead to suppose a relative movement of Java with regard to Sumatra may here perhaps be detected in the configuration of the sea-bottom to the north-east of the Talaud Islands. Here also, the bathymetric curves seem to indicate an eastward displacement over about 50 km of the block that carries the Talaud Islands with regard to the block carrying the Island of Mindanao. This would again correspond to a greater crustal shortening in the belt to the east of the first block. Although here also the evidence is rather vague, the repetition of the features pointed out for Strait Soenda gives some weight to the supposed relations.

The continuation of the belt towards the eastern peninsula of Celebes is easy to understand in connection with the supposition about the S.S.E. direction of the compressive force, and the same may be said for the eastward continuation of the belt south of Java towards the Kei Islands with the only exception of a local interruption near Soemba. The part between East Celebes and the Kei Islands, however, is more difficult to interpret. The gravity material here is not sufficient to feel sure about the details of the field; a north-south profile over West Ceram and more values in Boeroe and between that island and the Soela Islands and Obi would already be a help, while on the other side of the area a gravimetric survey of the eastern and south-eastern peninsulas of Celebes would likewise give important information. But even when the gravity field would be known in detail, it may be expected that an interpretation would be difficult because we have obviously a complication here of the general course of the phenomenon.

Originally the writer thought that the results might be emplained by the shape of the Australian continent and its prolongation towards Halmaheira; it may be expected that this continent would resist buckling and folding and that, in consequence of that, the buckling-belt had adjusted itself to the shape of this rigid block. The computation and study, however, of

the final results as well as the results of the investigations of UMBGROVE and KUENEN give reason to doubt this view. In the first place, it must be considered doubtful whether in the beginning of the Tertiary, before the folding and buckling took place, the deep basins of the Banda Sea did already exist and whether, therefore, the continental area of Australia did not continue towards Celebes. This question is treated by Umbgrove and Kuenen in chapters VI and VIII; they both give rather strong arguments in favour of this view. It is clear that when this would be right, the above explanation would lose its foundation.

But even when this view is not right, it seems doubtful whether the actual situation could be explained in this way. Looking at the configuration of the disturbances as it is known now and as it is given in the coloured map, we get the impression that, besides the compression from the N.N.W., a second compressional force must have acted on this area from the E.N.E. which must have caused the connection of the belt from the basin west of Laboeha towards the Kei Islands and likewise the continuation of the embranchment of East Celebes towards the south-eastern peninsula of that island. Neither of these parts could easily be explained by admitting only a compression in the main direction, i.e. towards the S.S.E.; the tentative attempt of the writer in this direction in "Ergebnisse der Schwerkraftsbeobachtungen auf dem Meere" (Ergebn. d. kosm. Phys. Bd II) must be abandoned in the light of our knowledge about the continuation of the belt in E. Celebes. The second direction of compression is likewise rendered probable by the morphology of the sea-bottom to the west and south-west of the island of Boeroe; the manifold ridges shown by the bathymetric map in this part of the Banda Sea suggest compression from the N.E.

It is hardly possible to determine the kind of deformation in these parts of the tectonic belt between Laboeha and the Kei Islands and in S.E Celebes. Considering the gravity results in the first of the two, we see that profiles 5 and 6 show a similar character, especially for the regional anomalies which we shall again adopt as the base for our discussions. The anomaly-curves are asymmetrical; in both profiles the positive anomalies are considerably larger to the left than to the right of the belt and the transition to the negative values is steeper on the left side. This points again to an asymmetrical root in this part of the belt. In the middle part between those profiles the field seems to be different, but the data are not sufficient to form a good opinion. The geological evidence on Ceram certainly points to folding, i.e. to a crustal shortening, but the character of the deformation of the crust as a whole cannot be derived and neither is it possible to say whether the shortening is great or small, although the latter seems more probable because of the small value of the negative anomalies to the west and the south of the island of Obi.

Less even than this can be said about the deformation in the south-east peninsula of Celebes. There are no gravity data at all in the axis of the belt and so neither the intensity of the shortening of the crust nor the character of the root can be determined. The only data on which the drawing of a continuation of the belt in this area is founded, are the geological data about folding and the evidence of the decrease of the anomalies near the coast. For the discussion of the geological data the writer may refer to Umbgroves study in the next chapter. It contains the important result that the folding must have taken place in the same period as that of the principal belt.

Taking these results together we must conclude that the evidence about the compression in this second direction is yet too incomplete to draw conclusions save that it has probably occurred simultaneously with that in the first direction. So there is no base for making further

suppositions about the reason why this compression appears to bring about two folded belts, one in Celebes and one over the island of Obi instead of one, or about the cause of the compression. With regard to this last question, it seems indicated to bring it into connection with the supposition of the previous chapter about a second tectonic belt over the Marianas and the Asia Islands. Further investigation in this part of the archipelago will, however, be needed, as well geologically as gravimetrically, before these problems can be attacked with a better chance of success.

We shall now consider a last point in connection with the belt of negative anomalies in the archipelago, the relation to the distribution of the volcanoes. It was pointed out in the previous chapter that in areas where the belt is curved, volcanoes are usually found on the concave side of the belt; they mostly occur in rows parallel to the belt and at a distance of about  $100-200 \, \text{km}$ . This is true for the row of volcanoes of the Sangir Islands with its prolongation towards N.E. Celebes and towards the volcano of Oena Oena; it is likewise so for the row of volcanoes from Ternate towards the south, and lastly for the row of volcanoes of the inner Banda arc which continues, after an interruption north of E. Timor, towards the lesser Soenda Islands and Java and Sumatra. This correlation might perhaps be rendered intelligible by the following reasoning.

If the crust moves towards a straight part of the belt, we must expect strong stresses in the sense of the movement but only secondary stresses in a sense parallel to the belt. When, however, the crust is moving from the inside of a curved part of the belt towards the belt, the stresses in the sense of the movement will be about the same, but parallel to the belt it is likely that tensile stresses will develop, because we may expect that the dimensions parallel to the belt must tend to increase when the crust moves towards the buckling zone. It appears admissible that these tensile stresses will facilitate the formation of volcanoes because of the corresponding release of pressure, although the area as a whole must be under strong compression.

A deeper study of the great and complex problems regarding the volcanic activity in the East Indies lies outside the scope of this chapter; the above suggestion is no more than an attempt to understand the curious correlation of its distribution to the tectonic belt. Is is certainly incomplete; the questions remains, for instance, to be answered why the volcanoes occur in rows that are more or less parallel to the belt, instead of being irregularly scattered over the area to the inside of the curve or of lying in radial rows as might be expected in the light of the above explanation. Is this caused by the presence there of an older zone of crustal deformation? The writer cannot attempt an answer to this question. He may refer here to what Umbgrove writes about the volcanism of the Archipelago on p. 149 et seq.

The subject of the investigation of the belt of strong negative anomalies is certainly not exhausted by the short discussion of this paragraph. Many further view-points will be found in the following chapters by Umbgrove and Kuenen, to whom the writer feels sincerely indebted for taking up this subject and for contributing to this publication.

### § 3. General discussion of the buckling-hypothesis.

The question may now be examined whether the hypothesis to which the gravity results in the Archipelago have led, has a more general validity for other areas where the Earth's

crust has given way to horizontal compression. This seems to be the case. Beginning with the few available gravimetric data, the strongest evidence in this direction is provided by the results in the West Indies, which we have seen in the previous chapter to show a remarkable similarity to those in the East Indies. As we shall come back to these results in chapter IX, we shall not further enlarge on them here.

Another instance is given by the results of the Italian gravity expedition of the "Vettor Pisani" in the Mediterranean. These results show a belt of negative anomalies in the Gulf of Taranto, which seems to be the continuation of the axis of the Italian Peninsula. The belt bends to the south-west along the coast of Calabria. So here again, a belt of negative anomalies accompanies the belt of tectonic activity. A further analogy with the results in the East Indies is provided by the field of positive anomalies that has been found in the basin of the Tyrrhenian Sea. A final discussion of these results will have to await the publication of the entire material and perhaps also a further continuation of the research in the adjoining areas, but the above results appear already sufficient to notice the similarity and to see that here also, the gravity field is more or less independent of the topography; the belt for instance does not follow exactly the axis of the Calabrian peninsula, but is shifted to the east. So, as far as the gravimetric evidence in other tectonic areas actually goes, it seems as if elsewhere the same kind of processes take place as in the East Indies.

We shall now consider our buckling hypothesis from a broader standpoint and examine whether it is in harmony with the generally recognized facts about the phenomena in geosynclines. In the sketch of the course of events that was given on p. 119, it was pointed out that the first stage must be expected to be the formation of a downward wave of the crust. This supposition is evidently in good harmony with the facts; the first stage of mountain formation is always admitted to be the formation of a geo-syncline. When the phenomenon proceeds and buckling begins to occur, the surface layer will be crumpled up and ridges will form that gradually lead to the formation of an archipelago. This again corresponds to the facts; it is for instance well-known that the Alps must have gone through an archipelago stage that probably has shown a similar character to the stage reached in this period in the East Indian belt, i.e. the belt indicated on the map by the blue colour on land and by the red colour at sea.

Since the beginning of the formation of the root there must exist a tendency of the belt to readjust the isostatic equilibrium by rising and this tendency must gradually increase when the root develops to greater dimensions. In the beginning this rising will carry along the adjoining zones beside the belt, but a moment must come when the shearing stress exceeds the strength of the crust and so, in a later stage, the belt will rise independently of its surroundings. As lateral compression of the crust will probably have the effect of strengthening it, it is likely that this independent rising will come into being in a period when the compression decreases.

The tendency towards readjustment of the isostatic equilibrium will probably not be the only cause of rising. We have hitherto neglected temperature effects but it is not likely that this is permitted, for in two ways the process of the buckling of the crust must disturb the temperature conditions. In the first place the root is pushed down in a lower position than the crustal material originally occupied and so it must gradually be heated up by the surrounding substratum. In the second place, as it is well-known that the crust is more radio-active than the substratum, the concentration of crustal material in the buckling belt must bring along a concentration of radio-active material and it must be expected that the temperature will tend to become higher than normal.

Both effects together make it likely that the root will partly or entirely become plastic and it seems probable that this will bring about an increase of volume. This must likewise cause a rising of the area. As, however, the thermic processes may be expected to be exceedingly slow, the rising will probably occur in a later stage of the whole phenomenon. A third cause for rising in a later stage may perhaps be found in another possible consequence of the disturbance of the temperature equilibrium; the formation of convection-currents in the substratum. We shall examine this possibility in the next paragraph.

So there are at least two or three causes for a rising of the tectonic area in a later stage of the phenomenon. This conclusion agrees in a remarkable way with the facts that have been discovered by the geomorphologists. It has been generally recognized that the morphological evidence in the existing mountain ranges compel us to admit these ranges to have only reached their great elevation after the folding had already subsided. This seems a support of the buckling hypothesis as it proves that the period of the greatest horizontal shortening of the crust has not been characterized by high surface features. So, as the crustal material must have disappeared somewhere, the only remaining possibility is that it disappeared downwards in the substratum. This is exactly what the gravity results in the East Indies show to be case and what has been formulated in the buckling hypothesis.

When the root becomes plastic, another consequence must be that under the influence of gravity it will, at least partially, flow away along the lower boundary of the crust. So we must expect that the root will become broader and that, therefore, the gravity field in older mountain ranges will no longer show the same narrow belt of strong negative anomalies but a broader zone of less intense deviations. This is undoubtedly the case. When we examine the case of the Alps, for instance, which have been thoroughly investigated in every sense and where the gravity field is known in detail thanks to the survey of NIETHAMMER, we see no evidence of a narrow strip of negative anomalies. Apparently isostasy has been reestablished in this area and the actual root of the mountain-system seems to have about the same width as the system itself. When, however, we examine the isostatic anomalies in the Alps more accurately, we see that this is not quite the case. In the central part small negative anomalies are found and in the adjoining zones small positive anomalies, and so this seems to point to a root that is still slightly narrower than the mountain-system itself. This conclusion may be derived as well from the results of the original isostatic reduction of the gravity material by Prof. NIETHAMMER 1), who applied a system of regional reduction by assuming that the compensation (of the Hayford-Bowie type) corresponds to the mean elevation of the topography computed over squares of  $8 \times 8$  km, as from the further studies by MARIETTE LEHNER 2) who applied the same system of regional reduction but with numerous other assumptions for the depth of compensation and for the dimensions of the squares over which the average elevation of the topography is determined. It follows likewise from the results of the investigations of Eero Salonen 3), who applied the Heiskanen system of isostatic reduction with different assumptions for the thickness of the crust.

<sup>1)</sup> Prof. TH. NIETHAMMER. "Die Schwerebestimmungen der Schweizerischen Geodätischen Kommission und ihre Ergebnisse", Verh, Schw. Naturf. Ges. 1921.

<sup>&</sup>lt;sup>2</sup>) MARIETTE LEHNER, Beiträge zur Untersuchung der isostatischen Kompensation der Schweizerischen Gebirgsmassen", Verh. Schw. Naturf. Ges. Band XLI.

<sup>3)</sup> EERO SALONEN, "Uber die Erdkrustendicke und die isostatische Kompensation in den Schweizer Alpen", Ann. Acad. Sc. Fenn. Serie A, T. XXXVII, No. 3.

All the curves which he obtains for the attraction of his different compensation assumptions show a broader curve in the central part and a smaller difference between the anomalies in the central part and in the adjoining zones than the observed gravity shows.

The question might be asked whether the negative isostatic anomalies in the central zone of the Alps could perhaps be brought about by the erosion, combined with a certain time-lag in the readjustment of the isostatic equilibrium after the removal of the eroded material. The writer does not think this explanation to be satisfactory, because in that case the deviation ought to show a clearer correlation to the distribution of the more elevated parts where the erosion is strongest. So it seems more indicated to look for the cause in a somewhat narrower root below the Alps than the mountain-system itself, and this would agree with the supposition that originally an analogous buckling of the crust occurred as that which has been supposed for the East Indies. A similar result has also been found in the Sierra Nevada, where the gravity observations of Sans Huellin, after the isostatic reduction of the results, likewise show a zone of negative values below the range. The same conclusion may here be drawn that the root is narrower than the mountain system itself.

It needs hardly be remarked that this conclusion about the Alps and the Sierra Nevada is contradictory to the often expressed view that the compensating root of folded mountain chains is formed by the downward bending of the crust under the weight of the packet of folds and overthrusts formed by the surface layers. This bending of the crust is then also held responsible for the formation of fore-deeps beside the mountain-system. This hypothesis, however, would involve a broader root than the mountain-system and the gravity results don't seem to allow such an interpretation.

In a still later stage of the geo-syncline, when the lateral compression of the crust has finally come to an end, erosion is the only outward agency that is stil active. This will continue till the whole area is peneplained, but as the isostatic equilibrium will probably be more or less maintained during this process, the lowering by denudation is partly counteracted by a rising because of the equilibrium readjustment. So the whole process of peneplanation must proceed more slowly and the erosion has to remove considerably more material.

We may, however, suppose with some reason that there are two factors that must accelerate the peneplanation. In the first place it may be assumed that the plastic root, after flattening out, will solidify and that this will bring about a decrease of volume and a corresponding sinking of the crust. In the second place, eventual convection-currents, if they did really come into being during the formation of the root, will probably cease when the thermic equilibrium is more or less readjusted by the flattening of the root, and this would likewise imply a sinking of the area.

So, besides the erosion, it is likely that there are other causes for a lowering of the mountain-range in the last stage. This may perhaps give an axplanation for a problem that has been raised by Jeffreys. On p 294 et seq of "The Earth" (2nd Ed.), he points out that there are several instances of old denuded mountain-ranges as e.g. the mountains of Wales and Scotland, the Appalachians and the Ural, where old sedimentary rocks are found in the central zones, although the denudation, according to what has been said, ought to have removed much more than the sedimentary cover of the crust, at least when erosion, counteracted by the readjustment of isostatic equilibrium, had been the only agents working. In that case only deep crustal layers ought to be found at the surface. When, however, a great part of the lowering had been caused by other processes, the presence of the sedimentary rocks could well

be understood. The buckling-hypothesis, moreover, may also play a part in explaining this feature. When the crust is buckling downwards, part of the surface-layer may be carried along with the main crust and so even strong denudation might still continue to bring sedimentary material to the surface. We may conclude that, in the light of these considerations, it is not necessary to assume a squeezing away, as Jeffreys does, of the intermediate layer of the crust in order to explain the lowering of the range and at the same time the presence of sedimentary rocks in these areas. Resuming our considerations about the tectonic history of the orogenic cycle in a geo-synclinal belt, we may say that the buckling-hypothesis is in good agreement with the geological and morphological evidence.

Another feature which may be mentioned in this respect, is the fact that most of the tectonic belts have a curved course over the Earth's surface. This is a curious fact in the light of the old theory which assumes the principal process in these belts to be a folding and overthrusting of the crustal layers towards the outside. Because the straight fold would take less energy than the curved fold, the first shape must then be expected to be normal. The situation is different, however, for the buckling hypothesis, according to which the main process is an inward buckling of the crust. In that case the curvature of the Earth's surface must give rise to another effect which diminishes the probability of a straight course. When the crust would buckle inwards along a part of a great circle, the root which thus would be formed, must be subject to compression in the sense of its length-axis because the dimensions in this sense have diminished. This compression must absorb energy and so it might be understood that a curved course with a slightly greater length than the straight course but without this compression in the root in the sense of the belt would use up less energy and would, therefore, be more likely to come into being. So a curvature of the belt can be well understood when the supposition of a downward buckling of the crust would be true.

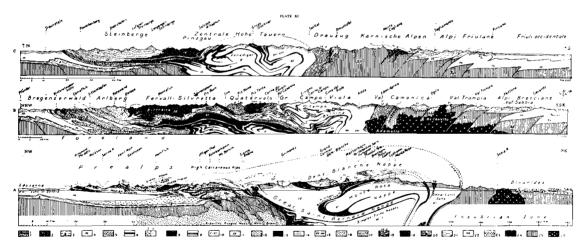


Fig. 22. Profiles through the Alps, A after E. Argand, B and C after R. Staub. (L. W. Collet: "The Structure of the Alps", 1927).

This hypothesis seems also to be compatible with the geological evidence that is found in folded mountain ranges. Argand's and Staub's profiles over the Alps, for instance, of which a few are reproduced in fig 22, show clearly that in the central zone the lower layer of the crust

disappears downwards. In the central zone we see thick folds that are strongly squeezed together and to both sides of this zone we see the autochtone layer of the crust, covered by horizontal overthrusts and showing fault planes converging downwards towards the central zone. This central zone coincides with the zone where the negative anomalies are found and where, therefore, the original buckling of the crust must be supposed to have taken place. The profiles seem to be in good harmony with this supposition. The folds in the central zone, i.e. the Pennide nappes in the western Alps, have the distorted shapes and the deep roots 1) that must be expected here, while the overthrusts to both sides, e.g. the Helvetide overthrusts, have the more regular horizontal cross-section, which agrees with the less disturbed position of the lower crust in these zones. It seems even as if we can trace in these profiles the rising of the structure which we have supposed to take place after the formation of the buckling root; it appears that the buckling zone, in rising, has taken along the adjoining zones to both sides.

According to the above view of the phenomenon, the whole structure must be more or less symmetrical, that is to say that it must be expected that overthrusts have been formed to both sides of the central zone. This opinion agrees with the more modern views about folded mountain ranges, expressed by BORN, STILLE and many other geologists. Only here and there, e.g. in the Alps, the overthrusts to one side have been more developed than to the other side and this has lead to the old view-point for the Alps, that the southern crustal block has overridden the northern block. Nowadays, the two-sided character of folded mountain ranges has been more and more recognized.

A more detailed examination of what is known about the geological history of the Alps does not seem to reveal features that contradict our hypothesis. The writer will try to summarize here, as far as he could master this difficult subject, what appears to bear on our problem. He wishes to confine himself to the western Alps with the Pennide nappes in the central zone and the Helvetide nappes to the north of them. The character of these two groups of folds is entirely different. The Pennide nappes, i.e. the St. Bernhard nappe, the Monta Rosa nappe and the Dent Blanche nappe are much older than the Helvetide nappes; they date from the Cretaceous or perhaps even from the Jura (Jenny) while the Helvetide nappes date from the middle Tertiary. The Pennide nappes have the character of folds, i.e. both limbs of the fold are usually well developed and the deformation has the plastic type. Although their horizontal dimensions are greater, their vertical dimensions are likewise considerable. The original sedimental layers that have formed these folds must have been thick and homogeneous; in many cases the thickness must have exceeded 5000 meters. These folds are evidently the first that have been formed in the geo-syncline after the main crust had given way and the horizontal compression of the crust has started. Their shape can undoubtedly be better explained by the hypothesis that the sedimental layer was carried along from both sides by the main crust and that this crust disappeared downwards in the central zone, than in the old way by assuming that the sedimental layer was more or less independently pushed together in an originally horizontal fold that was squeezed upwards and downwards in a later stage of the phenomenon. The thickness and homogeneity of the original sedimental layers points to their being deposited in a broad geosyncline in its first stage before any islands or ridges had been formed.

<sup>1)</sup> Root taken in the geological meaning as the lowest part of a fold with which it is connected to the body of the mountain-structure.

The Helvetide nappes have another character. They are less like folds and more like overthrusts. There is no middle limb connecting the crown of the upper limb with the inner edge of the lower limb and it is even unlikely that these two edges have been far apart in their original position as parts of the sedimental layer before the deformation took place. This can be concluded from the fact that this layer must have shown a gradual transition in thickness and facies from a neritic facies in the north to a bathyal one in the south and that the inner and outer edges of consecutive sheets don't show any marked difference in thickness or facies.

The shape of the Helvetide nappes is more regular and less deviating from the horizontal than that of the Pennide nappes; their deformation has more the character of faulting than folding. In facies the layers are more variable than the layers constituting the Pennide nappes. This is no doubt brought about by the later date of their deposition; in that time the geo-syncline must have reached the stage of an archipelago and so the sedimentation must have had a more irregular and more local character than in the first stage of the geosyncline.

It is generally supposed that the Helvetide nappes are the sedimental cover of the European shelf, against which the Alpine folding found its resistance. This cover is assumed to have been stripped off and pushed northwards by the action of the Pennide folds, which have partly overridden them. The buckling-hypothesis gives a somewhat different representation of this process. According to this hypothesis, the crust must have moved towards the buckling zone. There cannot be any doubt about the fact that this movement has had periods of stronger development and periods of quiescence; the fact that the Helvetide nappes have been formed so much later than the Pennide nappes is a clear proof of a period of subsidence of the compression between. We may safely admit, according to what has been said, that in that interval the Pennide nappes must have risen to great elevation above sea-level, forming in this way the ridges from which at least part of the sediments of the Helvetide layers were derived. These sediments must have been deposited in the adjoining seas that evidently must in general have been deeper near to the range than farther away. When then the compression started again, the sedimental layer must have been carried along with the main crust towards the central zone and must have been thrust under the Pennide ridges together with the main layer. This main layer must have disappeared downwards and enlarged the root. From this view-point, a Helvetide nappe ought rather to be considered as an underthrust than as an overthrust.

In the following periods, this phenomenon must have been repeated a number of times. With each period of quiescence the range must have risen and with each subsequent period of compression, a new sedimental sheet must have been pushed under the former one and a new Helvetide nappe been formed. This way of explaining seems to agree with the facts, the character of thrusting instead of folding of the Helvetide nappes and the absence of middle limbs. It is likewise in harmony with the fact that the highest nappe is the oldest one; this must indeed be the case when the above explanation is right. In the old explanation, on the contrary, this fact is difficult to make clear.

So, taking the evidence together, we see that the buckling hypothesis seems to be fairly adequate for explaining the major formations in the western Alps. The question may now be asked whether the geological data in the East Indies do show analogical features; this might allow to make still more sure about the parallellism of the phenomena in these two areas. Umbgrove's investigation makes it possible to give an answer to this question.

It has already been mentioned that all the islands in the belt of negative anomalies show great crustal folding with a strike generally coinciding with the axis of the belt. There is, however,

a remarkable fact which deserves our attention, viz the period of this folding. Umbgrove comes to the conclusion that, as far as can be ascertained, this period is the same for all the islands, i.e. the middle of the Miocene or, more accurately, Tertiary f 2 in the time-scale of LEUPOLD and  $V_{AN}$  DER  $V_{LERK}$  (see p. 141). The coincidence of all these foldings in the same period is of course satisfactory with regard to our hypothesis, but it is remarkable that the phenomenon has taken place so long ago. It appears unlikely that a root formed in the Miocene would still bring about the narrow belt of anomalies that has been found. If that could be the case, we should have to expect similar features in the Alps and in many other mountain-ranges; we have already considered the processes by means of which it may be explained that such features have for the greatest part disappeared in these mountain-systems. Umbgrove puts the question on p. 146. "May we now draw the conclusion that the extraordinarily strong negative anomalics, which are now met with, have come into being during a down-folding period of the Earth's crust, which we think must have occurred in the Miocene?" In the subsequent paragraph, he discusses the later geological history of the islands in the belt: in the first period after the folding rising and denudation, in the Pliocene sinking and sedimentation combined with the formation of "graben" in the central parts of some of the islands and, finally, towards the end of the Pleistocene, rising again and faulting. He concludes that a Plio-Pleistocene phase occurred after the Miocene folding, which in the upper layers expressed itself by the faulting just mentioned and which probably in the deeper substratum strengthened the negative anomalies. The presence of these strong anomalies in the present period would thus be explained. The seismic activity along the whole belt and the violence of the earthquakes are undoubtedly in favour of this view; they indicate that the belt is still the seat of active tectonic deformation.

So we may conclude that the crustal buckling is still continuing but that the upper layers of the crust in these islands are only affected by faulting; they don't show strong folding or other evidence of shortening in the present period. We have thus to assume that the crust is pushed under the islands where it disappears downwards, while the surface layers of the islands, probably because of their elevated position above the zone of compression, are not perceptibly squeezed together.

Now this whole history and especially this last phase shows a remarkable similarity to the tectonic history of the Alps as we have discussed it above. The folding stage in the middle Miocene can be identified with the formation of the central folds in the Alps, the Pennide nappes. On this period a rising of the ridges has followed in the same way as this was the case in the Alps, where likewise an archipelago stage occurred as a consequence of the rising. Lastly the present phase resembles what we may surmise about the formation of the Helvetide nappes, a thrusting of the crust with its sedimentary cover under the central packet of Pennide folds. So we may conclude that the history of the two areas seems to show a correlation and that they both can be adequately explained by the buckling hypothesis of the crust as it was exposed in these paragraphs.

This hypothesis seems also in good agreement with the views that are expressed in a recent publication "The Deformation of the Earth's Crust" by Walter H. Bucher 1). This important study contains a critical examination of the facts relating to the Earth's crust. It was not possible to take its results into account in this publication because nearly all of it had already been written when Bucher's book reached the writer, but one sentence may be quoted here, which

<sup>1)</sup> WALTER H. BUCHER, "The Deformation of the Earth's Crust", Princeton University Press, 1933.

shows that, at least in its major features, the opinion of Dr. Bucher corresponds to our hypothesis: On page 218 we find: "This slight change (meaning the substitution of "acid portion of the crust" for "crust") makes Meinesz' hypothesis practically identical with that developed by the writer on purely geological grounds. This convergence of views derived from independent sets of data strengthens the promise of their usefulness". A further study of Dr. Bucher's valuable and comprehensive work will be needed before a more complete statement is made.

The writer does not wish to go into the difficult problem of the cause of these great tectonic phenomena. If the interpretation of the gravity results in the East Indies in § 2 of this chapter is right, we have to do here with a movement towards the S.S.E. of this part of the Asiatic continent with regard to the floor of the Indian Ocean and Australia. As far as the gravity results allow a conclusion, it seems as if these last crustal parts have no relative movement; the absence of great folding along the west-coast of Australia points to the same result. The floor of the neighbouring part of the Pacific appears to have a movement relative to Asia as well as to Australia. In this part of the Pacific we have, however, to distinguish between two different parts. The relative movement of Asia with regard to the ocean-floor east of the Philippines has evidently about the same direction as that with regard to Australia and the Indian Ocean, i.e. to the S.S.E. The relative movement, however, with regard to the ocean-floor north of New Guinea has apparently a different direction as we have seen in § 2; the gravity results seem to indicate that this part of the Pacific has a movement towards the W.S.W. with regard to the East Indian Archipelago although probably this movement has not the same intensity as the first mentioned one.

For determining the relative movement of this part of the Pacific with regard to Australia, a gravity research along the north-coast of New-Guinea will be useful. At this moment the data are not sufficient for giving an opinion. The great mountain ranges of New-Guinea (see fig. 30) point to a movement towards each other and the presence of strong earthquakes indicates that this movement is still continuing, but it does not seem possible to come to a more definite statement.

The fact that the relative movements in the Archipelago point to forces in one or two directions only, makes it difficult to explain them by the contraction-hypothesis. If that were the cause of the phenomena, it seems likely that the compression ought to come from all sides, unless at least great irregularities in cooling, in thermic properties or in elastic properties would occur, but even in this last case the above distribution of the stress seems difficult to explain. The writer is tempted to look for the cause, or at least one of the causes of the relative movements in convection-currents in the substratum. In the next \ and in chapters I and IX the reasons in favour of the assumption of such currents are given and it may be admitted that, incase they occur, forces must be exerted by these currents on the crust. Nevertheless, this whole question is yet too speculative to allow any definite statement; a serious attack on this problem has to be deferred till more is known. A continuation of the gravity research may certainly be valuable in this connection. If in this way a distribution of convection-currents would be made plausible that would be in harmony with the forces that we have to assume for explaining the actual relative movements of the different crustal blocks, a better base for taking up the problem would have been provided. A difficulty, however, for assuming this cause as the only one is the periodicity of the movements which is indicated by the geological history of these mobile belts; this periodicity does not seem easy to reconcile with it.

## § 4. Positive anomalies in the East Indies.

With regard to the positive anomalies in the East Indian Archipelago, we can distinguish between three features. In the first place we have a general field covering the whole archipelago and giving a mean anomaly over this area of about + 20 mgal. A fairly undisturbed field is found over the Java Sea, i.e. between Java, Sumatra and Borneo. The mean anomalies over this part are + 24 mgal for the Hayford-Bowie anomalies, + 28 mgal for the Heiskanen anomalies and + 32 mgal for the regional anomalies.

In the second place there are strips of larger positive anomalies beside the belt of strong negative anomalies, they are clearly shown by the coloured map. One is for instance found outside the belt in the Indian Ocean and perhaps also one to the east of the Talaud Islands. In these areas we generally find a lesser depth of the ocean than at greater distances from the belt. This is shown e.g. by profile 2 of Plate II to the east of the Talaud Islands and by profiles 18, 19 and 20 to the west of Sumatra.

In the third place there are found fields of strong positieve anomalies in the deep basins of the archipelago, the Celebes Sea, the north-western part of the Banda Sea and the southern part of this sea. Perhaps the less extensive fields north of Banda and those north of New Guinea and north of the Asia Islands have also to be included in this class. A special feature of this class is the correlation of the anomalies to the depth; they are stronger positive for the deepest basins. The sign of this correlation distinguishes it from the second class. So the southern part of the Banda Sea has been brought under this heading although its parallelism to the belt of negative anomalies suggests its classification in the second class.

For the interpretation of the first feature, the general field of positive anomalies over the whole area and the regular part of this field in the Java Sea, we may have recourse to the last § of the first chapter. According to this § we have to choose from two possible explanations, a lateral compression of the crust and the existence of downward convection-currents in the substratum. As there is no evidence of any considerable sinking of the crust in the Java Sea, the latter explanation does not seem likely and so we probably have to fall back on the first one. This explanation, a lateral compression of the Earth's crust, can, moreover, well be adopted, for all the phenomena in the archipelago point to such a compression. Assuming the mean positive anomaly to be -|- 20 mgal, the thickness of the crust to be 30 km and assuming the compression to act in one direction only,formula 19 of page 41 gives a stress of 10.000 Kg/cm². This figure is more or less uncertain, firstly because we don't know exactly the thickness of the crust and secondly because of the fact that the mean anomaly has been derived from the sea-values only; it may change when gravity data will also be available on the islands.

The second feature, the strips of positive anomalies beside the belt of strong negative anomalies, can well be explained by the readjustment of the isostatic equilibrium. We have already pointed out that the negative anomalies must bring about a tendency towards rising and as long as the crust is able to stand the shearing stress, the adjoining zones must be carried along and must rise too. It appears indicated to adopt this explanation because we saw that these strips of positive anomalies coincide with zones of somewhat smaller depth and the amount of the gravity excess roughly corresponds with the excess of mass represented by the elevation of the sea-floor.

The last feature, the fields of strong positive anomalies in the deep basins of the archipelago, is more difficult to explain. The explanation has certainly to account for the correlation

with the depth because this correlation is too striking for being accidental. The same feature has, moreover, been also found in the deep basins of the West Indies, viz. in the Gulf of Mexico, in the sea west of Cuba and, as far as the few data go, in the Caribbean. So an accidental coincidence appears to be out of the question.

A valuable information with regard to these basins is given by the geological data. In the next chapter Umbgrove points out that there are many indications that these basins are recent formations that have come into being by a subsidence of areas that were originally continental or epi-continental. The same conclusion is arrived at by Kuenen in chapter VIII; he gives some morphological arguments in favour of this assumption. Lastly we find an analogical opinion expressed by several geologists (Waterschoot van der Gracht a.o.) about the Gulf of Mexico. Admitting the truth of this hypothesis we have to look for an explanation that can account for the positive anomalies as well as for the sinking.

This excludes the explanation that was given for the former feature, a readjustment of the isostatic equilibrium of the whole structure of the buckling-belt with the adjoining zones, because this explanation involves a rising of the area. An explanation by assuming that in some way the density of the crust has increased, e.g. by a change of state, and that, in consequence of this, the area has sunk away for readjusting the isostatic equilibrium, seems also difficult to admit. In that case it might be asked why the crust has not subsided enough for quite reestablishing the equilibrium. As the time which has elapsed since the formation of the basins is certainly not very short, geologically speaking, we ought to expect that the equilibrium would have entirely been readjusted.

So we are lead to the only explanation that the writer has been able to find for accounting for this combination of subsidence and positive anomalies, the developing of a downward convection-current in the substratum. The writer may here refer to § 9 of the first chapter, where he has discussed these questions at large and where he has shown that a downward current in the substratum must indeed bring about excesses of mass, which give rise to positive anomalies at the Earth's surface. At the same time the surface of the substratum above the sinking current must be lower than that above the rising current and so the subsidence of the area agrees likewise to this supposition.

The question arises whether perhaps these convection-currents might be responsible for the compression of the crust that is at the base of the whole tectonic phenomenon. Thanks to the investigation of UMBGROVE this question can receive an answer and this answer is in the negative. He proves clearly that the sinking must have occurred after the great folding process of the mobile belt in the Miocene. He writes on p. 154: "The present deep-sea relief of the East Indian Archipelago must have originated very recently, at least post-Miocene if not later, contingent with the formation of the very young Neogene faults which we can notice everywhere on the surrounding islands". So it is out of the question that the folding itself can have been caused by the convection-currents that are connected with the formation of the basins. This is not only true for the folding by the compression in the S.S.E. direction, but likewise for the folding in the second direction, the W.S.W., because both foldings have occurred in the same period, Tertiary f 2.

It cannot be denied that if this explanation is right and if convection-currents have developed in the Neogene, forces must now act on the crust that have not yet acted on it in the previous period and which, therefore, must have been added to the original system of forces. These added forces must converge towards the subsided basins. The writer cannot decide

whether there is any evidence of the working of such new forces. In those areas where the direction coincides with the old, no evidence may be expected, but where the directions differ, a change of the tectonic axis might be found. This depends of course of the question whether the effect of the added force is not insignificant with regard to that of the original one.

Knowing that the development of the convection-currents has occurred after the period of the principal folding, we are lead to the supposition of a causal relation of these two phenomena. A possible explanation of such a relation can readily be given. It has already been mentioned that the formation of the root of crustal material at the lower boundary of the crust must alter the temperature conditions, because it brings about a concentration of material that is more radio-active. So the temperature of the vicinity must also be heated up. It seems reasonable to suppose that this will lead to the developing of convection-currents in the substratum which will rise below the mobile belt and sink down in the adjoining areas. In this way the subsidence of these last areas could be explained at the same time as the rising of the belt. Before the current develops, the heating of the zone in the belt must already cause some rising of the surface of this area, but once the current sets in, this rising must further increase because the rising current brings warmer layers of the substratum in the place of cooler layers and so the temperature of the whole column increases. In the same way the sinking current in the adjoining area brings cooler layers in the place of warmer layers and the temperature of the column diminishes. So in these areas the surface must undergo a sinking although there was no cooling of the substratum here at the start.

The increasing temperature difference between the rising and sinking columns must further accelerate the current and so the whole process has an unstable character, i.e. in the beginning it increases more or less proportionally to its own intensity. After some time it reaches a stationary situation, which depends on the values of the viscosity, the coefficient of thermal expansion, the thermal diffusibility, the density and the original temperature gradient of the substratum and of the dimensions of the phenomenon. Until that stationary situation is reached, the rising of the belt and the sinking of the adjoining basins will continue. The whole process will strongly lag behind the period of folding in the tectonic belt which is its cause. This is in harmony with the facts in the East Indies; the subsidence of the basins must have occurred in a later period than the folding.

#### § 5. Other features in the East Indies.

The gravity field of the East Indies shows some other features besides the belt of strong negative anomalies and the positive fields treated of in the past §§. These features, however, are much weaker and so the present material is not sufficient for drawing conclusions from the gravity field only; for this purpose a more detailed gravity survey, supplemented also by values on the islands, would be necessary. The deviations show, however, a close correlation to the geological data in the archipelago which are treated of by Umbgrove in the next chapter. Umbgrove discusses this correlation and so the writer may refer to his chapter for the interpretation. He wishes only to add here a few remarks.

The further features disclosed by the geological data are in the first place a generally not intensive Miocene folding, treated by Umbgrove under II in chapter VI, along the west-coast of Sumatra, the south-coast of Java and continuing perhaps along the row of the Lesser

Sunda Islands; and in the second place a remarkable formation, denominated by Umbgrove as "idiogeosyncline" and treated of under IV in the same chapter occurring in the eastern part of Sumatra, the northern part of Java, the southern peninsula of Celebes, along the east-coast of Borneo and the north-coast of New Guinea (fig. 28, 29 and 30). We shall examine these two features consecutively.

As far as the Sumatra and Java parts of the first formation are concerned, no gravity data are available; a land survey will be needed for obtaining them. Perhaps the low value of the anomaly in Strait Bali, between Java and Bali, is connected with this feature, but this is yet uncertain as it may also be caused by the second feature, the idiogeosyncline in Java. To the east, however, over the Lesser Sunda Islands, a few values are available that may be connected with our feature, viz the anomalies of + 17 mgal on Soembawa and those of + 14, + 8 and + 17 mgal north of Flores, all taken from the coloured map, that is to say that these figures are the regional anomalies in those stations. Now we have seen in the previous chapter that the regional anomalies in the stations of the inner Banda arc, which is the continuation of this row of islands. likewise show a decrease with regard to the anomalies to both sides of the arc; this is cleary shown by the profiles 6, 7, 8, 9 and 10 of Plate II. So it appears as if the formation continues over these islands. Our examination of the profiles has further shown us that this decrease of the anomalies over the inner Banda arc is practically not found in the curves for the Heiskanen anomalies and so we have concluded that the feature is probably caused by a root at the lower boundary of the crust which compensates the ridge in the way as the Heiskanen method of isostatic reduction assumes it, i.e. by a root which is the enlarged and reversed image of the ridge on a scale of vertical enlargement of about  $4\frac{1}{2}$ . This conclusion would mean that the ridge is not purely of volcanic origin, but that there has been also a thrusting together of the crust. The station on Soembawa and two of the stations north of Flores that have been mentioned, show about the same results; on the transparent cover of the map we see that the Heiskanen anomalies in these station are likewise in better harmony with the neighbouring stations than the regional anomalies. So it is not unlikely that we may extend our conclusion to the whole row of islands, i.e. to the feature that we are considering here, the belt of not intensive folding in the Miocene, although of course neither the gravimetric data nor the geological data between the inner Banda arc and Java are sufficient to make sure of the connection between both areas. About the period of the Miocene folding. Umbgrove comes to the conclusion that it may have occurred in the same period as the great folding in the other belt.

Here our conclusions end and speculation begins. Has this ridge been formed in the above period or is the slight folding in this period an afterworking of an earlier and greater tectonic phenomenon? The writer would be inclined to consider the last possibility as the most likely. We could in that case better understand that the isostatic equilibrium has been nearly readjusted and also that this belt has shown a slight folding in the same period that the other belt underwent the strong buckling phenomenon. If it is an afterworking in an old folded belt, we may admit that it can resist sufficiently for transmitting the great stress needed for the great phenomenon in the second belt. If it was a folding in its beginning, it is difficult to see why the crust did not continue to buckle here instead of doing it in another parallel belt.

The second feature, the idiogeosyncline. has its course for a great part on land and so here also the absence of gravity data on the islands is a draw-back for getting a good idea about the way in which this formation expresses itself in the gravity field. The present material can nevertheless give important indications. As Umbgrove remarks, there can be no doubt that

we find a decrease of the anomalies over this belt; this is clearly demonstrated by the low values, in comparizon with neighbouring stations, found to the north of Sumatra, in Strait Soenda, in Soerabaja, to the south of Madoera and in Balikpapan, that is to say in all the stations in this belt. It is likewise in harmony with the torsion balance results of the "Bataafsche Petroleum My" on Java, which have been kindly communicated by this company; Umbgrove mentions a few values in the next chapter.

This result seems to be in good agreement with the geological data. The belt has apparently been subject to subsidence during a great part of the Tertiary; in some areas the subsidence began already in the Eocene and it lasted till the Pliocene. The sedimentation in this belt was so strong that the sea never had a great depth; during the greatest part of its duration it must have been shallow sea. So we now find thick layers of sediments, in most areas of a thickness of many thousands of meters. These sediments have a lower density than the average density of the crust and so they must bring about a defect of attraction. This is in harmony with the above results but it cannot be the only cause of the gravity defect that is found. A sinking of the crust must likewise give a displacement of the substratum by crustal material, forming in this way a root of crustal material at the lower boundary of the crust. This will also contribute to the defect of attraction.

The available data are not sufficient to check this reasoning by a computation of the anomaly that in this way ought to be brought about, but a rough estimate shows that it cannot be far wrong. So we are led to the supposition that in this belt the crust has been bending and that the trough has been filled in with sediments. Gravity is certainly contradictory to another imaginable supposition, a downward buckling of the crust covered by a thick sedimental layer. This interpretation cannot be adopted because the root cannot be much larger than what the simple sinking would bring about, for else the defect of attraction would have to be greater. This conclusion is corroborated by the fact that no great folding has occurred in this belt. It is true that to the end of the period, after the sedimentation had finished, a slight folding by lateral compression must have taken place, but this does not mean more than an insignificant shortening of the crust. It is likewise in harmony with the discovery of Umbgrove that in some places the belt is interrupted. This could not well be explained when the crustal shortening had been great along this belt.

Umbgrove concludes that the way in which the sedimentation has taken place, proves that the sinking of the crust in this belt is not caused by the sedimentation itself, although this may have played a part in it, but that there must have been an endogene cause. This leads us to the supposition that we have to do here with a wave-formation of the crust by lateral pressure of the kind we have investigated theoretically in § 8 of the first chapter. If this is true, it would be a proof that these waves really do occur and this supports our hypothesis concerning the buckling-phenomenon in the other belt, which we likewise assumed to begin by such a wave-formation. As this second belt is over a great part of its length parallel to the buckling belt, we may even suppose that these two waves are belonging to the same wave-deformation of the crust, as fig. 19 on page 119 shows it; the horizontal dimensions seem certainly to agree in order of magnitude to the theoretical length of the waves derived in chapter I p. 48. As the compression continued, the outer wave has apparently given way and has buckled downwards, while the second one continued to resist as it might be expected, because once the crust has given way in one place, it is unlikely to break in another place at the same time. The filling by sediments must probably have favoured the development of the deformation in the second belt and

deepened the downward wave. This whole theory seems to fit well in the system that has already been discussed with regard to the other belt.

Returning to the gravity evidence in the archipelago, it may be pointed out, as Umbgrove does in the next chapter, that the belt appears to continue from Java towards S. Celebes. A further survey with more stations in this area may give certainty about this point, as it may too with regard to other parts of the belt, e.g. the continuation of the belt north of Sumatra, the connection between Java and Sumatra and the eventual continuation of the part of the belt along the east-coast of Borneo. As this belt contains the oil-fields of the archipelago, this continuation of the survey may be important for a further prospection.

At the end of this chapter about the interpretation of the gravity results in the East Indies, the remarkable correlation may be emphasized, which has been found between the gravity field and the geological investigation of Umbgrove. The gravity field gives indeed a faithful representation of all the more recent phenomena. The results in the East Indian Archipelago are a strong proof that gravity cannot be interpreted without the geological and geomorphological data and that on the other hand the gravity field can give valuable information to geology and geomorphology.

A further point which seems worth while to draw attention to, is the conclusion that the gravity field, as it is observed on the Earth's surface, seems to be the combination of effects of many different layers of the Earth. The superficial layers give the local irregularities found by means of the torsion-balance which have not been treated of in this publication. The deeper layers of the crust do likewise affect the field as e.g. in the idiogeosynclinal belt. The deformations of the crust at its lower boundary, where roots are formed and light crustal mass thus displaces the heavier substratum, have perhaps the most important effect on gravity; the tectonic belt in the archipelago is a strongly pronounced instance of this. Lastly we find probably gravimetric evidence of still deeper disturbances in the deep basins of the archipelago; if our conclusions are right we have to do here with the effect of convection-currents in the substratum. So the gravity field appears to be the combination of a great many effects together and we need the indications from geology and geophysics for the unravelling of its meaning.

#### CHAPTER VI.

## The Relation between Geology and Gravity Field in the East Indian Archipelago

by

### J. H. F. UMBGROVE.

#### Introduction.

When such intensive isostatic anomalies are met with in an area as those found by Vening Meinesz in the East Indian Archipelago, it is an obvious task for geologists to trace the reflection of the anomalies in its geology. As the result of some conferences I had with Vening Meinesz in the summer of 1931, I undertook a critical study of the literature of the Tertiary of the East Indies with the pre-conceived intention of summarising the available data in such a way, that this could form a basis for a comparative study of the geology and gravity field of the East Indian Archipelago. The results of this study of the Tertiary have been summarised and drawn on a map, on which areas with an identical or at least analogous geological structure and history, have been indicated with a similar notation. This map, together with the data on which it is based, was published towards the end of 1932 (Lit. 14). 1)

Afterwards some additions and corrections on account of new data were given (Lit. 15 and lit. 16).

The following article may be regarded as an elucidation of the map (Plate IV) on which both geological data (I - IV) and gravity observations are represented.

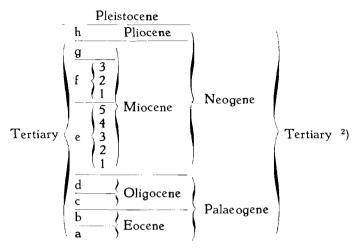
In consideration of the fact that the gravimetrical anomalies in the East Indian Archipelago are much more pronounced even than in a tertiary folded mountain chain like the Alps it seemed that a natural and safe procedure would be to attempt establishing a correlation between the younger tertiary geological history of the East Indian Archipelago and is observed isostatic anomalies.

The pretertiary history, which moreover for evident reasons is not so well known, will not be discussed in this article.

It is interesting to be able to establish some striking coı̈ncidences between the tertiary geology and the deviations of isostasy in this area now that the final computations and reductions of the gravimetric data can be compared with the geological synthesis, mentioned above.

<sup>1) &</sup>quot;Lit" refers to literature references at the end of the chapter.

Although I do not intend to give many stratigraphical details, it will be unavoidable to indicate certain horizons of the Tertiary now and then. For this purpose I shall use the well-known letter division of the East Indian Tertiary. 1)



On the map there occur a number of different geological notations drawn on the islands, by which areas differing mutually in geological structure and history during the Tertiary, are differentiated.

I shall treat these successively (I—IV) and mention their contingent connection with the results of the maritime gravity research.

I.

In the first place I shall treat those areas which are indicated by a blue colour 3) on the map, Pl. IV. These regions belong to the same type of geosyncline, showing three tertiary cycles of movement; the most important, very intensive folding occurred in the Miocene. They are all situated in the belt of strong negative anomalies at sea indicated by a red colour on the same map.

The data for these islands, which have been compiled in Lit. 14, could be considerably improved on and added to thanks to the help of Dr. Fr. Weber. Prof. Dr. J. Wanner and Ir. H. Terpstra, who have been so kind as to place at my disposal their entirely new and, as yet, unpublished data brought to light by their investigations in the Moluccas, respectively Timor and the Mentawei islands. For complete data see Lit. 16. The following is only a short survey. Summarising, we can give the following outline for the islands situated within the zone of strong negative deviations of isostasy (compare Pl. III. and IV.)

<sup>1)</sup> See. W. LEUPOLD and I. M. VAN DER VLERK. "Tertiary", in MARTIN-Feestbundel. Leidsche Geologische Mededeelingen, Deel V, 1931 and I. M. VAN DER VLERK en J. H. F. UMBGROVE. Tertiaire gidsforaminiferen. Wetenschappelijke Mededeelingen Nr. 6, 1927.

<sup>2)</sup> The vertical distances between the horizons are arbitrarily taken and bear no relation to the geological times involved. The same may be said of Pl. III.

<sup>3)</sup> The colour is of a more or less intense blue according to whether the extent is more or less certain. An analogous remark is aplicable to the other geological notations.

 Lower-tertiary folding (i.e. post-Eocene and before Tertiary e<sub>5</sub>), found on Rendjoewa, Timor, Tanimber, Ceram, Boeroe, the Eastern arm of Celebes

found on Rendjoewa, Timor, Tanimber, Ceram, Boeroe, the Eastern arm of Celebes and Boeton;

probable for Nias, the Mentawei islands, Rotti and Koer, wanting on Groot-Kei.

2. Miocene period of principal folding (in Tertiary f, probably  $f_2$ ), where the intensive folding was in several places so strong, that overthrust masses were formed (indicated below by D),

found on the Mentawei islands, Rendjoewa, Timor (D), the Tanimber islands (D) the Kei islands, small islands between Kei and Ceram (D?), Ceram (D), the Banggai Archipelago, the eastern arm of Celebes, Central and S.E.-Celebes;

probable for Nias, Rotti, Letti (D) and Boeton.

3. A late tertiary cycle of movement; after a period of denudation followed subsidence (sedimentation of pliocene and pleistocene marine strata) and ensuing upheavals. The folding is hardly perceptible or very weak and still going on; only locally strong movements (E. and Central Celebes). In the central part of some islands or groups of islands there is a clear formation of troughs or graben (S);

Found on Nias, the Mentawei islands, Rendjoewa, Rotti, Timor (S), Tanimber islands (S), Ceram (S), Boeroe (S?), the Banggai Archipelago, the eastern arm of Celebes, Central- and S.E. Celebes.

As regards the oldest "posteocene" folding the following must be noted. In a number of places (see Pl. III.) the data do not allow a narrower limitation of time than: post Eocene and before Tertiary  $e_5$ . However according to Dr. Weber a weak unconformity within Tertiary  $e_5$  seems to occur on the Tanimber islands (lit. 16 p. 28). A weak folding, also in Tertiary e (viz. post Tertary d and pre-Tertiary  $e_5$ ), occurred on Soemba as well and a folding post Tertiary d and pre-Tertiary  $e_5$  was found on Boeton. And finally, a posteocene weak folding has been found in Bantam (S. Java) in Tertiary e (see below, p. 152). These data led me to place the "posteocene" folding provisionally in Tertiary e (see Pl. III.) also for those areas where the time could, as yet, not be defined within narrow limits.

The transgressive position of Tertiary e<sub>5</sub>, the so-called Beboeloe transgression <sup>1</sup>), which has been noted in so many places, is also rendered intelligible by this assumption.

The principal folding of these areas took place during the Miocene, and so it is not only older but it has also been much more intensive than in the idiogeosynclines (see Pl. III.) mentioned later on (Sub IV.).

First of all I want to go into the time and the type of this principal folding.

On the island of Timor rocks containing Lepidocyclina of which the age is probably Tertiary e, have been met with as component parts of one of the overthrust sheets. At any rate it is apparent that, on Timor, the principal folding, during which large overthrusts were formed, took place at least after Tertiary e.

For the Kei islands we must, on the ground of Dr. Weber's investigation, conclude to an intensive folding after Tertiary e, (probably a part of the younger Miocene — Tertiary f — also belongs to the folded series) and before the Pliocene (Tertiary h).

<sup>1)</sup> See: LEUPOLD and VAN DER VLERK lit. 7, and see J. H. F. UMBGROVE: Neogene foraminifera of Sg. Beboeloe, Pasir (S. E. Borneo). Summary in English. Wetenschappelijke Mededeelingen No. 5, 1927.

On the strength of Weber's new data, exactly the same conclusion is reached for the Tanimber islands; a very intensive folding after Tertiary e and before Tertiary h.

Dr. H. M. E. Schürmann, chief geologist of the "Bataafsche Petroleum Maatschappij", kindly supplied me with the following data on the island of Ceram: "It can be demonstrated that the main folding on Ceram took place between the "young Miocene" and the "Pliocene" During this folding overthrust masses moved in a N.E. direction. The pliocene sediments, occurring along the N-coast and in the Masiwang- and Bobot-troughs are principally of marine facies and locally they reach a thickness of 2000 m. In Mid-Ceram these pliocene strata are weakly folded, in E. Ceram especially vertical movements seem to have taken place in post-pliocene time".

The negative deviations of isostasy are very intensive between Halmahera and the Northern arm of Celebes, and we see that the isogams show a westerly branch, running straight on to the Eastern arm of Celebes. There too, we find strongly kneaded Tertiary. The principal orogenesis by which there originated large overthrusts and "nappes", took place, according to Koolhoven, during the Miocene (after Tertiary e<sub>5</sub> and before Tertiary h).

In Central Celebes and on the N. E. peninsula an intensive young miocene folding has been discovered 1).

Though the final maps and descriptions have not been issued yet, on Boeton <sup>2</sup>) the succession of the three tertiary cycles of movement which we have outlined seems to be very probable (see Lit. 14 p. 809; Lit. 15 p. 34; Lit. 7 p. 645; Lit. 18 p. 216).

To these data are now added TERPSTRA'S stratigraphic sections for the Mentawei islands,

The eastern part of Central Celebes and the eastern and southeastern peninsulas are situated within a zone of negative isostatic anomalies. It might therefore be expected that the tertiary history of these regions would show analogies to other islands within the negative zone (Lit. 16 p. 21, note 2). Indeed this seems to be the case: VAN DER VLERK and DOZY pointed out, namely, the occurrence of marine miocene strata (Tertiary e<sub>5</sub> and f) in the S.E. peninsula. "The oldest of these samples is of Tertiary e<sub>5</sub> age; so that here again as in so many other places in the archipelago we observe a transgression of this stage (Beboeloe transgression)".

.... "The transgression evidently took place over a folded region consisting of serpentines and the cretaceous formation" (Lit. 18 p. 216).

According to Brouwer (Lit. 2 p. 84) the miocene strata, deposited unconformably on folded pretertiary formations, have also been very intensively folded.

The age of this folding may be deduced more correctly in northern Central-Celebes (Posso). BROUWER mentions that the older strata of the Neogene are strongly folded; on the other hand the younger Neogene has hardly been disturbed (Lit. 2 p. 116, also p. 61).

From the study of VAN DER VLERK and DOZY it is clearly demonstrated that Tertiary f still belongs to the strongly folded Tertiary where as strata younger than Tertiary f have only been slightly folded if at all (Lit. 2 p. 114, Lit. 18 p. 216).

Therefore this geological history of the Neogene corresponds with that constructed by KOOLHOVEN for the N. E. peninsula. The pliocene cycle of movement has manifested itself rather intensively in the N. E. peninsula.

2) I am indebted to Mr. C. A. D. BOTHE for the data on the occurrence of Eocene on Boeton marked in Pl. III,

<sup>1)</sup> Recently the results have been published of explorations carried out by BROUWER, HETZEL and STRAETER in Celebes (Lit. 2). As early as 1930 BROUWER pointed out that their "observations permit the supposition of a tertiary folded range with its convex side to the west and with a general trend which bends approximately in the direction of the present eastern and southeastern peninsulas" (Lit. 1 p. 341). In this zone basic and ultra-basic igneous rocks, cherts and mesozoic limestones predominate. To the west follows a zone of crystalline schists. An "important divisional line with regard to the different rock types runs about from north to south through the central part of Celebes" (Lit. 1 p. 339), the zone west of the divisional line being characterised by the predominance of granitic rocks. The divisional line itself is characterised by a strongly mylonitic zone.

Siberoet and Sipoera. He noted strongly folded Tertiary, still including Tertiary e, but on which Pliocene rests discordantly. So, again, the same period of folding.

What is known of Nias points in the same direction and the same holds good for the Nicobars and the Andamans.

The data about Rendjoewa show a marked resemblance to the picture which has already been given of a dozen islands or groups of islands. Moreover, the data for the Tertiary of islands such as Rotti and Letti, which are, it is true, still very fragmentary, do not furnish us with reasons to conclude to a principal folding of the Tertiary during another period.

So there is now sufficient "converging evidence" to come to the conclusion that on the series of islands which can be followed from the Nicobars via Nias and Sipoera, across Timor to Ceram and from the East to the S.E. of Celebes — the only areas in the East Indian Archipelago 1) of which a very intensive miocene folding is known (which in many places has given rise to the formation of overthrusts) and which are situated within the zone of strong negative deviations of isostasy — the principal period of folding must be considered to have been after Tertiary e and before Tertiary h.

Although it cannot be proved, it seems to me that for the following reasons we may suppose this period of folding to have occurred during Tertiary f. We know that after this miocene folding and before the transgression of the Pliocene a long period of erosion and denudation must have followed. (About this more can be found on p. 146) Now there are reasons to suppose that Tertiary g represents a relatively much shorter period of time than Tertiary f (See lit. 15 p.38, 39). Then, it is not impossible that the lowest horizons of the transgressive "pliocene" must still be considered as Tertiary g. (A few relatively low percentages of recent molluscs on Timor — which are, however, based on too few species to be entirely conclusive — might i.a. beconsidered as pointing in this direction; a fauna of the island Klein Kei mentioned by Weber, but not yet described, may also prove to belong to this) Then, as has already been mentioned above, part of Tertiary f was probably included in the folding and finally, this intensive folding itself must, of course, have lasted an appreciable period of time.

All this renders probable that the principal folding has occupied part of Tertiary f.

Only more accurate palaeontological data than are now avaible will enable us to bring this period of time within narrows limits.

This period will then probably prove to agree with the orogenetic period of the, for the rest, less intensively folded areas namely Tertiary f 2. We shall presently treat this more exhaustively sub II. In Pl. III I have supposed and drawn them as follows 2).

<sup>1)</sup> HARLOFF (Lit 5) claims to have found miocene nappes in S. Java. His opinion will be discussed in more detail on page 150.

<sup>2)</sup> These results are also of importance for Zoogeography. For we may expect that the greatest extension of land and consequently the best chances for the spreading of land- and freshwater animals existed during the periods of subaeral erosion and denudation towards the end of and following a period of folding. For the Southern Moluccas the times important for the spreading of land- and of freshwater animals have been: (this may be read directly from Pl. III) shortly after the Palaeogene, that is the Lower Miocene (Tertiary e) and afterwards the end of the Miocene; then followed, during the Pliocene, a period of "sauve qui peut", and finally, in the Pleistocene an expansion of the surface of land and islands took place again. The most important period of spreading demanded by Zoologists in this part of the Archipelago is a so-called pliocene one (See: L. F. DE BEAUFORT Zoogeographie van den Indischen Archipel, 1926). It goes without saying that with this indication of "Pliocene" the Zoologists do not attempt to fix an exact age. From Pl. III it is evident that in all probability the period after the principal miocene folding is meant. As has already been observed, the position in which it has been drawn in is not entirely certain. More precise data will perhaps necessitate a slight transposition upwards (in Tertiary f, or possibly in lower Tertiary q).

The facies of the marine Tertiary is littoral or neritic. Some globigerina marls may perhaps be called hemipelagic (It must, however, be remembered that globigerina marls may sometimes be deposited in very shallow water; Rutten, Lit. 10 p. 708, has given a very clear example for the East Indian Archipelago and also pointed this out elsewhere, Litt. 11).

The data concerning the thickness of the strata are not yet very numerous. Weber estimates the whole strongly folded Palaeogene-Miocene series of the Kei islands, at about 2000 metres. The pliocene (and possibly also part of the youngest Miocene) of the Lesser Kei islands he estimates at about 1200 (— 1500?) metres. Molengraaff estimated the thickness of this series on Timor at more than 500 m.

KOOLHOVEN gives a thickness of about 1000 metres for the intensenly folded Miocene of the eastern arm of Celebes; the Pliocene can reach a maximum thickness of 3000 metres, or even more. On Ceram the Pliocene may locally reach a thickness of 2000 m. (According to data kindly furnished by the "Bataafsche Petroleum Maatschappij").

The figures which Terpstra mentions for the Mentawei islands are as follows: Miocene at least hundreds of metres, Pliocene tens of metres.

Although the data are few in number it would seem therefore that the geosynclinal subsidences which may indeed be noted here in the Tertiary have been in general less strong than those met with in most of the idiogeosynclinal areas (see sub IV).

These facts can only be observed on the sometimes widely scattered islands which are painted blue on the map. The form and extension of the strongly negative zone allows us to form an idea of the original form and extension of these geosynclines <sup>1</sup>). Judging from this shape one might feel inclined to call them monogeosynclines <sup>2</sup>). Their structure however, has been changed so radically since the Tertiary that to day only the islands mentioned above are accessible to geological study. A considerable part of the geosynclines — which will be discussed later on — were submerged to great depths not earlier than postmiocene (e.g. the deepsea basins N. and S. of Timor and those on both sides of the string of islands W. of Sumatra) In this way secondary basins and ridges in the tertiary geosyncline originated <sup>3</sup>). In this light we cannot call the strongly negative zone a monogeosyncline, but on the contrary it shows a strong resemblance to Schuchert's polygeosyncline <sup>4</sup>). Provisionally I will therefore classify these regions as polygeosynclines <sup>5</sup>).

<sup>1)</sup> Only approximately so because the extension of the negative zone to day is probably smaller than it must have been originally.

<sup>2) &</sup>quot;The true geosynclines as originally defined by Hall and Dana, which finally give rise to but one synclinorium, are exemplified by the Appalachian geosyncline. They are long comparatively narrow, deeply subsiding, but always shallow-water, smaller, primary geosynclines, situated within a continent along the inner side of borderlands. They should hereafter be known as monogeosynclines, because they are the simplest of geosynclines". (SCHUCHERT lit. 12 p.195).

<sup>3)</sup> see sub IIIc.

<sup>4) &</sup>quot;The typical example is the Cordilleran primary trough, out of which have arisen the Cordilleran Intermontane and Ancestral Rocky Mountains geanticlines and the subsiding Pacific and Rocky Mountain sequent geosynclines. They may be known as the polygeosynclines, the prefix suggesting that several geosynclines are combined." (SCHUCHERT lit. 12 p. 196).

<sup>5)</sup> The earlier, pretertiary history of the regions will not be discussed here.

The explanation which Vening Meinesz has given for the occurrence of the strongly negative areas — sinking of the crust of the earth until the limit of elasticity has been passed and folding downwards occurs, by which a root of light sial material is folded down into the sima and at which only relatively thin surface layers are folded upwards and form overthrust sheets — is supported by the surface structures and the geological history of these areas.

By this coincidence of geology and gravity results we gain at the same time an indication of the time during which this phenomenon took place. For the period of the most intensive folding must obviously coincide with the occurrence of the downward folding as supposed by Vening Meinesz.

May we now draw the conclusion that the extraordinarely strong negative isostatic anomalies, which are now met with, have come into being during a down-folding period of the earth's crust, which we think must have occurred in the Miocene (Tertiary  $f_2$ )?

For an answer to this question it is necessary to examine somewhat more closely the later history of the strongly folded East Indian areas. Let us first consider Timor. The miocene "period of folding and tilting", Molengraaff writes (Lit. 8 p. 224), "was most probably followed by a period of prolonged and considerable denudation, because it is observed that a later-tertiary formation of neogene age is found resting unconformably on the much denuded (peneplainized) older formations".

During the time when these pliocene and plistocene sediments were deposited, trough faults and basins (graben) began to form on Timor (Lit. 8 p. 224, 225), well nigh parallel to the

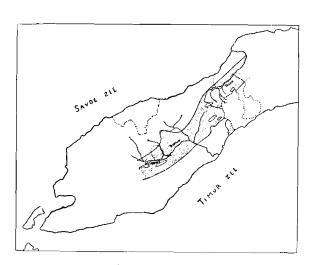


Fig. 23.

Sketch map, showing the area of the upper-tertiary (pliocene) deposits in Central-Timor (after Molengraaff).

longitudinal axis of the island (fig. 23) The pliocene and pleistocene deposits are not or very slightly folded, with the exception of a steep distortion of the upper Tertiary at the sides of the basins or "graben". They have been raised to a considerable height, however, during the later Pleistocene, in central Timor e.g. to 1280 metres above sea-level.

Very briefly we can summarise these movements as follows: after the period of intensive folding follows a period of elevation combined with denudation and levelling of the landscape. Then, during the Pliocene, subsidence, formation of faults (graben) and, finally, towards the end of the Pleistocene, again raising above the level of the sea and faulting. Thus the miocene period of folding is apparently followed by a clearly marked

phase of movement which is, however, not characterised by folding, but especially by faulting.

It is therefore conceivable that a Plio-Pleistocene phase occurred after the Miocene upward-folding, which has expressed itself, in the already strongly folded upper layers, by the faulting mentioned just now; on the other hand it has, in the deeper substratum, probably

strengthened the negative anomalies, which must already have been weakened, to the strong negative which has now been found.

Likewise as on Timor, a trough-shaped depression in the Pliocene, appeared on the spot were the Tanimber islands are situated now. This depression was filled up with marine

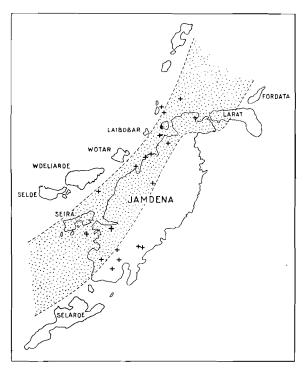


Fig. 24.

Sketch map, showing the pliocene trough in the Tanimberislands. Mudvolcanoes are indicated by crosses
(after data from Dr. Fr. Weber).

sediments, resting unconformably on the intensively folded older Neogene. Fig. 24 composed according to data furnished by Dr. Weber (lit. 16 p. 29) gives a diagrammatic picture of this. 1)

As a third example (fig. 25) we may examine the Kei-islands somewhat more closely. According to Weber's data (Lit. 16) neither Eocene nor Pliocene occurs on the western zone, Koer and Fadoh; continual sedimentation from old Eocene to within the Miocene (at least Tertiary-e, probably also part of Tertiary f) took place in the central as well as in the eastern zone.

After the ensuing period of intensive folding which is met with in the whole of this area (see Pl. III) Groot Kei was raised and remained above the level of the sea; in the central zone, on the other hand (Klein Kei and Tajando) a trough-shaped subsidence was formed, marine Pliocene was deposited and slightly folded towards the end of the Pliocene. 2)

I want to point out in a few words that upraised plio-pleistocene marine deposits are also known in other areas situated within the intensive negative zone.

We know, moreover, that their origin was, in Ceram and perhaps also in Boeroe, attended with the formation of analogous graben. 3)

Thus e.g. Rutten says in his summary (lit. 11 p. 751) "We have seen that in contrast with the pre-pliocene movements, the plio-pleistocene movements manifest themselves through the entire area of the Southern Moluccas, as if they were faults and epirogenetic uplifts; it is only dealing with the latest geological history of Ceram that I pointed out how, since the deposition of the pliocene Fufa-beds, a very slight folding with great amplitude, has occurred there".

<sup>1)</sup> Published by consent of the "Bataafsche Petroleum Maatschappij".

<sup>2)</sup> For further particulars see Lit. 16.

<sup>3)</sup> For further particulars see Lit. 16.

As signs indicating that this latter cycle of movement has not yet been terminated it may further be mentioned that according to  $\mathbf{W}_{\text{EBER}}$ , submarine ridges occur connected with or as a

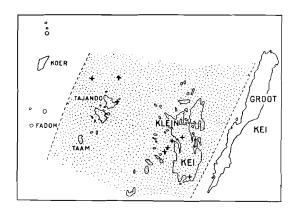


Fig. 25.

Sketch map, showing the pliocene trough in the Kei-islands.

Mudvolcanoes are indicated by crosses

(after data from Dr. Fr. Weber).

prolongation of upper-pleistocene folded ridges in the young coral limestones of the Kei islands in the zone of klein Kei — Tajando and in the S. W. part of the Tanimber group. Moreover I can mention the following, taken like the above from a written communication of Dr. Weber, as it is certainly valuable to quote the opinion of such an eminent student of the Moluccas: "On Klein Kei and Tajando as well as on the islands between, there occur a number of mud volcanoes and diapyrlike uptrusions and three new islands have been formed during the last three centuries (1699—1852) (of which two have again disappeared)".

"It is remarkable that the zone of strong negative anomalies coincides in the West with the arrangement of the mud volcanoes on

Timor, Samoea, Rotti, and, in the North with the zone where, in Ceram the mud — and salt water springs, which are unknown in the other part of this island, are situated along the eastern shore".

"Already in 1926 in his paper "Schlammvulkane als Anzeichen gegenwärtiger Gebirgsbildung" Lozinski pointed to the occurrence of the mud volcanoes as an expression or sign of a recent formation of mountains 1). Perhaps it may thus also be said that the areas

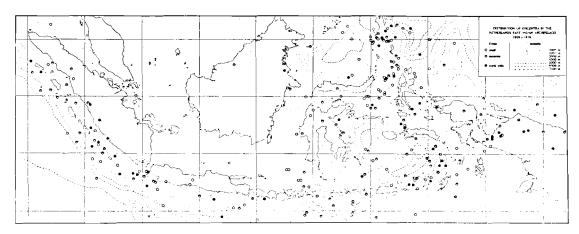


Fig. 26.

Distribution of earthquake epicentra in the East Indian Archipelago (after Dr. S. W. Visser, Lit. 17).

<sup>1)</sup> See also: St. ZUBER. L'activité des vulcans de boue en connection avec la structure des plis gaséifères (See J. ZWIERZYCKI Toelichtingen bij Bl. XIV and XXI. Jaarboek Mijnwezen 1927. Verh. I).

mentioned do indeed point to a labile zone of the earth's crust with a minimum resistance and the actual movement of a mountain chain in statu nascendi".

In this connection I may point out that there may be some connection between the thickness of the pliocene strata of these areas and the intensity of the negative effect, as may be ascertained by comparing figures for thickness, given above, with the map (Pl. IV).

Besides, not only is the thickness of the pliocene sedimentation of the Mentawei islands small, but also their raising above the level of the sea is relatively slight.

Finally it is of importance to note that many centres of strong tectonic earth-quakes are situated exactly in the zone of strong negative anomalies (fig. 26); in this zone, not a single volcano occurs on the other hand (fig. 27).

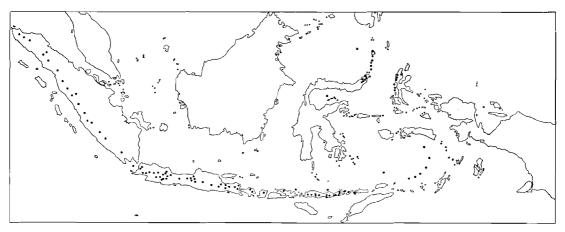


Fig. 27.

Distribution of the active volcanoes in the East Indian Archipelago (after Dr. Ch. E. Stehn, Lit. 13).

Indeed, a region enormously compressed and underlain by a downfolded root must be unfavourable for volcanic action; on the other hand strong earthquakes may be expected in this zone.

II.

Parts of Western Sumatra and the South of Java besides Bali, Lombok, Soembawa, Flores and Soemba, have been indicated with a separate (green) notation (Pl. IV). A miocene not-intensive folding is known from these regions. The gravimetric profiles seem to show — in accordance with this — a trough, which, however, is much weaker than that appearing so strikingly in the zone of strong negative anomalies. Moreover, there occur in this strip some local geological differences which have been indicated with the different notations a, b, c, d, e and f.

When comparing fig. 27 with Pl. IV it is obvious that many of the active volcanoes occur in the zone described sub II and in its prolongation. These regions must have risen above sealevel since Upper-Miocene time (see Pl. III) Such a "geanticlinal" ridge may be expected to be favourable for the origin and maintenance of volcanic action 1).

<sup>1)</sup> The same may be said of Celebes' northern arm (see sub IIIa) and of the Western part of Celebes' southern arm (see Pl. III and Lit. 14 p. 806) where subrecent volcanoes occur.

In many volcanic districts the volcanoes and the craters clearly show an arrangement along lines (faults) which in general run diagonally with regard to the trend of the volcanic zone (see Chapter VII § 4). The latter in its turn is roughly parallel and on the concave side of the zone of strong negative anomalies.

The distribution of volcanic phenomena in the East Indian Archipelago shows, however, still many unsolved problems, worthy of a special study, in which also the distribution of the tertiary and the pleistocene volcanism should be considered.

#### II a and b.

In the Eastern part of the South of Java (Djiwo) a horizon of the Miocene (viz., Tertiary  $f_3$ ) which was hardly folded if at all has been met with in an unconformable position on a series of older miocene deposits (Tertiary  $f_1$ ) which have been regularly folded (during Tertiary  $f_2$ ) and which in their turn rest discordantly on marine Eocene. 1)

We may probably suppose that an analogous scheme is applicable to Bali and Lombok and perhaps also to Soembawa. On Flores, however, marine sediments seem to have been deposited during Tertiary e (or part of it) too.

So we may conclude that in the eastern part of the South of Java, which has been mentioned, and a continuation of this strip across some islands East of Java, there is a (not intensive) folding which took place during Tertiary  $f_2$  (notation IIa on the map; see Pl. III).

Whether the other, post Eocene unconformity which has been noted on Java (Djiwo) also occurs on the islands east of Java cannot possibly be ascertained as the section of the Tertiary is not exposed to this depth.

A folding of which the time could be fixed as post-Tertiary d and pre Tertiary e<sub>5</sub>, is known of the island of Soemba (see Pl. III; full particulars are to be found: Lit. 14 p. 820). <sup>2</sup>)

Perhaps this folding may be parallelled with the post-Eocene and pre-Miocene folding which has been noted elsewhere also (See also the summary given on p. 142).

The younger Tertiary has been slightly folded on Soemba (Kemmerling mentions slopes of  $10^{\circ}-14^{\circ}$ ). It is not impossible that in this we must still see the weak expression of the same period of folding which on Java (Djiwo) was fixed as Tertiary  $f_2$ . Data do not, however, furnish us with absolute certainty, so that for the present I have indicated Soemba with a different notation (II b on Pl. III and IV).

<sup>1)</sup> I may mention here a recent publication by HARLOFF on the Lho-Oelo mountains in Southern Mid-Java (Lit 5). Eocene has been found resting discordantly on pre-tertiary (in which overthrust "nappes" of young cretaceous age have been demonstrated). As Tertiary f rests unconformably on the Eocene there are some obvious analogies to the Djiwo-profile, mentioned above. According to HARLOFF's opinion very intensive orogenesis took place in the Miocene (Tertiary f) forming enormous overthrust sheets. Some quotations may elucidate his opinion. "On account of tectonic arguments", writes HARLOFF (loc. cit. p. 25-26) these sediments (i.e. shales, sandstones and very coarse conglomerates, consisting of erosion products of Pretertiary, Eocene and the lower breccia-horizon) must be of young-Mid-Miocene age" and further on: "these sediments, being undoubtedly younger than Eocene, are locally covered by this (Eocene) formation e.g. West of Kedoenglo"...... If this be true the abnormal sequence of these strata must be caused by one or more faults probably thrustfaults. It seems to me, however, that we need not follow HARLOFF, where he concludes (loc. cit. p. 40) that the whole complex of tertiary strata existing at that time, must have been thrust over the pretertiary area forming an enormous overthrust mass or "nappe". (See also the criticism by Rutten in: Geologie en Mijnbouw nº. 6 Septemb. 1934).

<sup>2)</sup> See also pag. 202 of a recent publication by C. M. B. CAUDRI: Tertiary deposits of Soemba, Dissert. Leiden, 1934.

Anyway neither Soemba nor S. Java or the islands east of Java appear to have been included in the very intensive folding (post Tertiary e) of the areas mentioned sub I. As far as can at present be seen from the gravimetric data it appears that Soemba is situated outside the zone of strong negative deviations of isostasy.

As has already been said before (sub I) it is quite possible that the period of the very intensive miocene folding of the areas mentioned sub I (situated within the zone of strong negative anomalies) has been the same as that during which the much weaker folding (during Tertiary  $f_2$ ) took place in the South of Java. I have drawn it as such in the graphic summary (Pl. III).

The gravimetric profiles which Vening Meinesz could construct for the series of islands east of Java (Pl. II), are in good accordance with this; they show namely a clear trough or bending, which, however, is much weaker than those appearing so strikingly in the zone of strong negative anomalies.

#### II c.

In this connection it is of importance to point to the results of the mapping of the S.W. of Sumatra, which have appeared recently. Van Bemmelen writes namely that Tertiary e occurs in the surroundings of Kroeï; it is clearly folded; on these miocene strata a series of layers rests unconformably, the thickness of which is about 800 metres (including an andesitic lahar agglomerate) and the age of wich could be fixed as Pliocene on the evidence of marine molluscs (± 50 % living species) (lit. 6, 1933, p. 22—24).

We can hardly speak of a folding of these Pliocene sediments. The youngest movements have, while forming many faults, caused upheaval and tilting of these young tertiary strata through which there originated a slope of some degrees towards the Ocean (l.c. pag. 49). Therefore the principal period of folding must also have occurred at least post Tertiary e and pre Tertiary h (see Pl. III) and it appears to be rather intensive along the western coast near Kroei; in some places near Kroei the layers are even perpendicular (l.c. p. 48).

In this last respect besides in the stratigraphic section, the surroundings of Kroeï show resemblance to the neogene history of areas situated within the zone of strong negative anomalies. Now it is indeed remarkable that, exactly here, the strongly negative zone comes very close to the coast of Sumatra; according to the Heiskanen reduction this area would even be situated within it.

We may therefore certainly regard it as situated on the boundary between the "blue" and the "green" notation.

#### II d.

In the southern part of the Residency of Benkoelen marine upper Tertiary of pliocene age lies unconformably and not folded on older formations.

It has, however been proved that the Pliocene layers of Kroeï (see sub II c) form a direct continuation of the young Neogene of the peninsula of South Benkoelen (lit. 6 1933, p. 19).

Now, it remains an open question whether in the South of Benkoelen, Miocene originally also occurred, which either disappeared entirely by erosion before the transgression of the Pliocene, or has been preserved locally but withdrawn from view.

It is possible, probable even, that this southern part of Benkoelen has also had a history which, during the Miocene was similar to that of the Northern surrounding of Kroeï (see sub II c). Consideration of the data given below (II e and II f) is of importance in this connection.

#### II e.

In the western part of the South of Java (Bantam) a thin sheet of unconformable Pliocene occurs as in the South of Benkoelen.

In Bantam (sheet Bajah) according to KOOLHOVEN (lit. 5) a folding of the older Tertiary, took place (including Palaeogene of about 3000 metres thick and lower Tertiary a) during Tertiary e and before Tertiary e<sub>5</sub> (l.c. p. 52). He places, however, the principal folding after the sedimentation of the so-called Badoei layers which occupy part of Tertiary f. According to his opinion (see his schedule) this series does not fully include Tertiary f3. Of the foraminifera which are mentioned to substantiate his opinion the Lepidocyclina and Miogypsina, Alveolinella bontangensis, Cycloclypeus annulatus and C. biplicatus 1) and C. transiens 2) prove the age to be Tertiary f but do not prove it to be Tertiary f<sub>3</sub>. So it is still possible that the folding (strong in the South but weak in the North of shoet Bajah) which has been observed, may be parallelled with those occurring in Tertiary f of Djiwo; but we lack certainty about this (l.c. p. 53). Tertiary g is entirely lacking in this area of the map. With the exception of remains of temporary transgressions in the southern part, Tertiary e5 and Tertiary f occur only in the northern part and increase in thickness towards the North. According to Koolhoven we have here arrived at the southern boundary of the idiogeosynclinal area of northern Java. In the South Pliocene which has been slightly folded was deposited unconformably on older Tertiary. The whole area is strongly dislocated by faults.

#### II f.

On the other hand it seems that in extensive areas along the West Coast of Sumatra only special horizons of marine Neogene occur transgressively, which are slightly folded if at all and which have only been interrupted by movements causing tilting and fault structures.

As far as our knowledge goes at present we know e.g. that along part of the West Coast of Sumatra only one special horizon of the Miocene (Tertiary f) rests unconformably on a pretertiary substratum, and has been only slightly folded if at all. Thus e.g. it has been met with in the valley of Impoe, near Tambang Sawah and in the so called basins of Korintji, Asai Rawas and Kesiro.

Mr. Terpstra was so kind as to give me further information:

"For Mangani, Salida, and Mocco-Mocco it holds good that the tertiary rocks are only "secondarily folded and broken by eruptions; in general the strata show a dip of  $5^{\circ}$ — $10^{\circ}$  "mostly towards the western coast".

<sup>1)</sup> See TAN in; Wetenschappelijke Mededeelingen Nr. 19, 1932 Schedule V sub 6 and 4.

<sup>2)</sup> See TAN in; De Mijningenieur nr. 12, 1930, p. 337.

For this reason these areas might be given the same notation as e.g. the Aroe islands (III) where we likewise know only the occurrence of nearly undisturbed transgressive Neogene. The possibility that a detailed geological survey may reveal analogies with the S.W. of Sumatra, induce me to indicate them, as yet, with a different notation.

#### III a and III b.

We must now mention a few areas where, during the Tertiary, only a relatively thin sheet of neogene limestones has been deposited on an older substratum, and which has subsequently not been folded or only very slightly.

As deposits in the shallow sea of the tertiary Sahulshelf we may regard the Neogene of the Aroe-islands, a part (the S. E. peninsula) of N.W. New Guinea generally called the "Bird's head", Misool and probably also Obi.

Also in the region of the present Northern arm of Celebes it seems, according to Koperberg, that during the Tertiary, only limestones of a special Miocene horizon (Tertiary  $e_5$ ) have been deposited, and are slightly folded if at all  $^1$ ).

These areas (notation IIIa on the map, Pl. IV) are gravimetrically distinguished by fields of positive anomalies of isostasy, as is also the so-called Soenda shelf of which we know that, during the Tertiary it was for the greater part a continental or shelf area 2) across which epicontinental seas transgressed only locally and very temporarily (notation IIIb on the map Pl. IV).

#### III c.

Let us now regard the areas of strong positive deviations of isostasy, which roughly coincide with part of the most important deep-sea basins within the Archipelago, the two Bandasea basins with the Gulf of Boni, the Gulf of Tomini, the sea of Celebes with a Southern branch to the Macassar Straits, and the Soeloe Sea.

If we want to obtain insight into the geological past of these areas, this is in some degree rendered possible by the contemplation of the islands surrounding them.

<sup>1)</sup> Recently, however, strongly folded Eocene was found in the "neck" of Celebes (Lit. 2) In this connection it is interesting to recall the finding by TER BRUGGEN of Eocene in phyllitic facies in W. Borneo (De Mijningenieur 1932, p. 56—57). Perhaps future investigations will prove that the northern peninsula of Celebes shows stronger points of resemblance with e.g. South-Java and should better be indicated with a green notation. This question cannot yet be settled at present. Gravimetrically the conditions are analogous.

<sup>2)</sup> The greater part of Sumatra, Malakka, Borneo and the groups of islands situated between them, formed part of an extensive continental area during the Eocene.

The geosynclinal basins of great subsidence and sedimentation were formed there — the so-called idiogeosynclines IV). Where, along the West Coast of Sumatra marine neogene rests unconformably on an older folded pre-tertiary substratum, this latter must be considered as remains of the lower tertiary continent of Soenda land, to which the Southern part of Sumatra's East Coast, the Riouw Archipelago, Western Borneo, Banka, Billiton and the Karimoendjawa islands, belonged too.

The origin of the neogene geosynclinal basin of the South of Sumatra (Indragiri, Djambi, Palembang) has only apparently broken the connection between the continental substratum of East and West Sumatra, mentioned just now. In reality it has subsided for the greater part and has become the locally very deep bottom of that idiogeosynclinal basin.

It appears to me, to be of great importance, that the tertiary marine sediments of these islands have a neritic and littoral character, as was already pointed out above in another connection.

From this follows that the sediments have been deposited on a pre-tertiary substratum which during the Tertiary was never situated deep under the sea; in other words: the seas were shelf seas or epicontinental seas. Moreover we must remember that the tertiary epicontinental marine sediments had originally a greater extent than they show now, as is evident from the fact that in several places (Timor, Soemba, W. Celebes, Ceram, etc.) the strikes are intersected by the present coastlines, and that in general the islands rise from the sea with steep broken shores. (see pag. 167 and Lit. 8 pag. 123, 129).

Then, pl. V shows the large areas which fall at present within the boundaries of the 500 m isobath and which, therefore must, at least now be considered as shelf regions.

In short, the facts show us that not only have the tertiary sediments as we see them now been raised above their original level, but also that the present islands are no more than fragments of a former much more extensive shelf, or in part, perhaps of an area situated above the level of the sea. Not only does the group of islands Bali, Lombok, Soembawa, Flores form an appendage of the Soendaland from which it is separated by not very deep sea- straits, but during the Tertiary, it was an area which, like Soemba, was flooded by a sea that was at the utmost shallow, that is epicontinental. On Timor occur mesozoic and palaeozoic sediments of entirely different facies (among which there are bathyal sediments and even cretaceous deposits which are generally considered to be typically abyssal) which have been heaped up to overthrust structures during the Miocene, and the same is the case e.g. on the Tenimber islands. Even here the Eocene, Miocene and Pliocene sediments, have only a littoral to neritic character. Not a single indication that the area belonged during any period of the Terticry to deep-sea area is to be found here either; on the contrary, at the utmost it was once situated only slightly below the surface of the sea.

The present deep-sea relief of the East Indian Archipelago must have originated very recently, at least post-Miocene if not later, contingent with the formation of the very young neogene faults which we can notice everywhere on the surrounding islands. Shelves, partly perhaps also continental areas must have subsided over considerable amounts, and have given rise to the formation of the deep-sea basins in their present shape.

Vening Meinesz — as is explained by him in this publication — comes to the conclusion that in the areas of strong positive deviations of isostasy a considerable subsidence of the bottom must have played a part. In this respect also the results of geological and gravimetric observations prove to bear each other out.

We are thus led to a conclusion analogous to that of Verbeek and others who explained a deep sea like the Banda-sea by a, geologically young, subsidence of the bottom (compare Chapter VII, § 1). In passing we may observe here that, according to the explanation given before (sub I) only those tertiary areas which are situated within the zone of intensive negative isostatic anomalies can be compared with a tertiary folded mountain chain of alpine character. (compare Chapter VII, § 2).

#### IV.

The tertiary basins of strong subsidence and sedimentation where, amongst others, the most important oilfields are situated, are indicated by a purple colour <sup>1</sup>). In literature they have mostly been given the name of geosyncline. A short time ago, I treated their structure and history in some detail (lit. 15).

Here I want to point out the following six characteristics and, where necessary explain them.

1. Their subsidence, filling-up with sediments and the ensuing period of folding, have been terminated geologically speaking and compared with other geosynclines within a very short time.

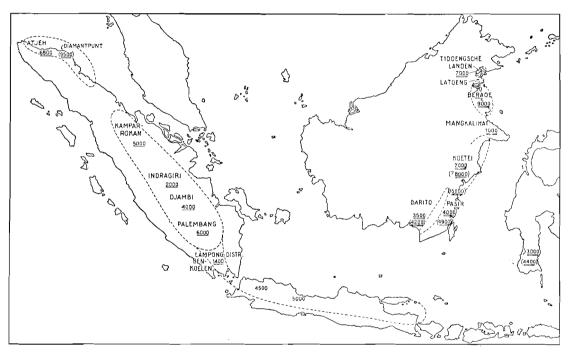


Fig. 28.

Idiogeosynclines in the western part of the East Indian Archipelago. Explanation in the text.

In fig. 28 a sketch map of the most important of these basins is given; the figures indicate the thickness of the Neogene sediments; the figures between brackets indicate the thickness of the whole Tertiary. When the figures are underlined the "geosynclinal" subsidence began during the Miocene, when double underlined during the Eocene: when not underlined (in casu Java) the time of the beginning of the subsidence is not known with sufficient

<sup>1)</sup> The colour is of a more or less intensive purple according to whether the extent is more or less certain. An analogous remark is applicable to the other geological notations.

certainty <sup>1</sup>) The subsidence and sedimentation lasted in each case until the end of the Tertiary, after which followed a period of not-intensive folding, with the exception of the western portion of the southern arm of Celebes, a region which must have risen above sea level since the Miocene (Tertiary  $e_5$ ), See Pl. III, <sup>2</sup>).

These figures clearly show that the intensity of sedimentation and the amount of subsidence which can be deduced from it, have been much more marked in the Neogene than in the Palaeogene. Moreover in those regions, where sedimentation lasted from Eocene to Pliocene, we observe two cycles of subsidence and sedimentation. As an illustration: in general the sequence of strata in the Lower-Tertiary of Borneo is 1. basal conglomerate 2. sandstones 3. marls 4. limestones. They have an aggregate thickness of 1000 m and are overlain by the neogene cycle which has a total thickness of several thousand of metres.

2. These tertiary basins of sedimentation are filled principally with neritic and partly with hemipelagic deposits (perhaps part of the globigerina bearing marls and limestones may be called bathyal); also limnic, lacustric and terrestric deposits sometimes form an important part of the sediments (See Pl. III).

Abyssal deposits do not occur at all.

- 3. The strong subsidence and sedimentation begins everywhere in continental regions. Thus e.g. the "geosynclinal" series begins with fluviatile-terrestric sedimentation in the Baritobasin (S.E. Borneo) and the South of Celebes. In other places the lowest layers of the geosynclinal series are formed by marine, i.e. neritic sediments of a transgressive epicontinental sea.
- 4. These tertiary "geosynclines" of the East Indian Archipelago do not form continuous strips or zones, but they are basins or troughs with a strong subsidence and sedimentation.

That the three basins of sedimentation situated along the East coast of Borneo have each had their own individual development and were separated from each other by submarine ridges (notation IVb on the map Pl. IV) has been conclusively demonstrated by Leupold and Van der Vlerk (Lit 7). The individuality of these areas manifests itself clearly in the differences of their stratigraphic profiles (See Pl. III) and is also evident from the facies and thickness of the sediments deposited on the ridges between them (See Lit. 14 and 15).

Atjeh, the South of Sumatra and the North of Java may also have belonged to three different basins of sedimentation.

The difference between the development and the stratigraphic profiles of the Tertiary in Atjeh and the South of Sumatra has already been pointed out more than once (Lit. 7 and 14). This argument alone already pleads for the individuality of these geosynclines.

No Neogene is to be found along the sides of Lake Toba. Therefore a contingent connection between the trough of Atjeh and that of the South of Sumatra would have to be looked for entirely to the East of Lake Toba.

There, however, the older layers are hidden by a sheet of volcanic ejectamenta.

The latest publications of the Geological Survey, devoted to Sumatra, are of especial importance for the question whether a connection exists between the geosynclines of

<sup>1)</sup> See Pl. III and for further data and particulars see Lit. 14.

<sup>2)</sup> The stratigraphical column of Java on Pl. III is only a generalized scheme. In reality the Javanese geosyncline has a very complicated structure and locally there may have been areas above sealevel even in Upper Tertiary times (see e.g. the data given by VAN Es. Lit. 4, for Sangiran, Sondé, Ngawi etc.; see also Lit. 14, p. 784, 785).

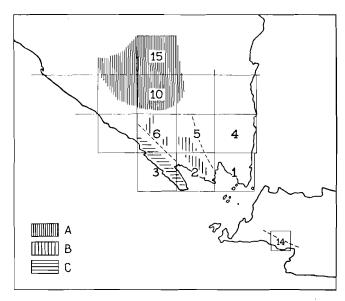


Fig. 29.

Sheets of the geological maps of S. Sumatra and Java (Bantam);

A Idiogeosyncline of S. Sumatra; B. probable temporary extension of A;

C. pliocene transgression

Central to Southern Sumatra and the North of Java (Lit. 6) On the accompanying fig. 29 the situation and the numbers of the maps that have been published are indicated. VAN BEMMELEN (Lit. 6 1932) has stated as his opinion that the Southern boundary of the geosyncline is to be found on map 10 (Batoeradja). In the areas of maps 1 and 4, no Tertiary has been met with at all; the pre-tertiary substratum covered with velcanic material has been found locally. On maps 2 and 5, bordering on the West of these areas, however, marine Tertiary belonging to a certain horizon of the Miocene, viz. Tertiary e5 could be mapped, resting transgressively on granite and old schists. A thickness of between 1000 and 1800 metres has been ascertained locally. So perhaps

there has existed an, albeit narrow, not deeply subsided and only temporary geosynclinal connection between the South of Sumatra and the North of Java, via the peninsula situated between the bays of Semangko and Lampong. To the West, in the South part of the residence of Benkoelen, only a thin transgressive layer of unfolded marine "Pliocene" has been met with, resting unconformably on a pre-tertiary substratum.

Van Es (Lit. 4) has presented strong arguments that the Straits of Madoera form a submarine continuation of the North-Java geosynclinal area. In Bantam Koolhoven mapped the Southern margin of the Javanese geosyncline. (Lit. 5, see 14 on fig. 29).

These East Indian tertiary basins of subsidence and sedimentation show some points of resemblance with Schuchert's type of monogeosyncline, but there are some very striking dissimilarities. In the first place the shape, which, where it is in some degree indicated, is like a basin (more or less drawn out). Secondly, the period of filling up is very short. Then the folding is not intensive. A monogeosyncline finally results in a real folded mountain chain, such as the Appalachians; the strata of the East Indian tertiary "geosynclines" under discussion, however, have been compressed into folds of a much milder character. Besides short anticlines and domes, overturned folds, faults and even thrust faults did develop, but the structure is not comparable to that of folded mountain-chains with large overthrust masses. The period of folding of all the geosynclinal areas treated up to now occurs towards the end of the Tertiary (Plio-Pleistocene). In a sense these areas show the characteristics of what Von Bubnoff (lit. 3) has called an unstable shelf, with which e.g. he puts the mesozoic and tertiary history of Western Europe over against a so called stable shelf-area like Central Russia where the marine sediments, which cover the old central European continent unconformably, show much smaller thickness

and a hardly perceptible orogenetic influence. The characteristics of S.E. Borneo are similar to those of such an unstable shelf.

Schriff's monogeosyncline on the one hand, and Von Burnoff's "Unstable Shelf" on the other, ought to be sufficient to indicate the points of similarity and dissimilarity of the East Indian tertiary areas of great subsidence and sedimentation. In a systematic nomenclature they must be placed between these two. If a name must be chosen, it seems to me that the independent, basin-shaped morphology of the Indian areas and the enormous thickness which the sediment-layers posses locally, and which they have obtained in a geologically, relatively very short time and finally the type of folding furnish three arguments to regard them as a special type of geosyncline. A short time ago, I introduced the term basin geosyncline or idiogeosyncline for these areas (Lit. 15).

5. Formerly I already pointed out (lit. 15) that the weight of the sediments cannot possibly have been the cause of the subsidence of the East Indian idiogeosynclines, but that the cause must be of an endogene nature 1). As a result of the subsidence the accumulation of thick sediment-layers became possible. This is evident from the stratigraphic sections of the Tertiary as well as from the palaeogeography before the origin of the basins.

Thus e.g. the lower layers of the geosyncline in Palembang, Djambi and Indragiri are formed by the neritic (litoral) neogene limestones (Tertiary e<sub>5</sub>) of a shallow sea, which was, however, in its extension not limited to that area — which during the ensuing Neogene is subject to a strong subsidence — but covered, unconformably, a much more extensive area. This in itself can not be explained without supposing that, in consequence of an endogene cause, a subsiding movement continued in certain places only. Neither can it be explained in another way that, after the accumulation of sediment-layers, the thickness of which shows great divergences for different basins of sedimentation, the subsiding movement diminishes gradually and that afterwards the whole of the contents of the basic is folded together <sup>2</sup>). As an instance I add the description which Rutten (litt. 11 p. 384) gave in 1927 of the movement of the idiogeosyncline in the district of Palembang:

"The first transgression indicating the origin of the geosyncline, begins with the littoral lepidocyclina limestones; soon, however, the geosynclinal subsidence surpasses the speed of the sedimentation and reef-limestones can no longer grow there; in a rather deep, but still continually subsiding sea, the Goemai layers, which are 3000 metres thick, are deposited. Gradually the sedimentation begins to gain on the geosynclinal subsidence and, during the period of the Lower Palembang layers, quite a number of sandy sediments, containing the fauna of a quiet but shallow sea, originate by the side of argillaceous sediments. With the beginning of the Middle Palembang layers, the geosynclinal subsidence becomes relatively so small that the sediments deposited acquire a continental character, and at the time of the Upper Palembang layers this continental character continues, to end in the folding of the Neogene. Thus the geosynclinal subsidence was greatest during the Lower Neogene, diminished gradually and at last — shortly before the beginning of the folding — finished entirely" (See also Rutten lit. 11 p. 399).

<sup>1)</sup> It is generally known that in 1859 JAMES HALL attributed the subsidence to the weight of the accumulating sediments whereas J. D. DANA, who introduced the name of "geosyncline", regarded not the filling up with sediments, but movements in the crust of the earth as the cause of the subsidence.

<sup>2)</sup> Of course the author does not want to deny the influence which a growing weight of sediment in the geosyncline would exert.

6. Gravimetrically the situation of the idiogeosynclines or their probable submarine continuation (IVc on the map Pl. IV) is indicated by a clearly decreasing deviation of isostatic equilibrium, which, generally being positive in the East Indies, sometimes becomes slightly negative here.

A striking "halo" of this type has been found round the supposed submarine continuation of the geosynclinal basin of Atjeh  $^1$ ) A contingent connection between the geosynclinal area of the South of Sumatra and the North of Java, must, as has been explained before, be sought for across the central peninsula of the South of Sumatra, situated between the bay of Semangka and that of Lampong. Exactly on the prolongation of this peninsula we see the isostatic anomaly diminish from + 62 milligal in the South of the Straits of Soenda, and + 56 milligal in the Bay of Batavia to + 18 milligal. It is remarkable to note the surroundings of the Straits of Madoera, according to  $V_{AN}$  Es a submarine remains and continuation of the North Javanese idiogeosyncline, is characterised by - 12, + 6 and + 6 milligal. An interesting addition can be given, thanks to the kind communication of Mr. A.  $V_{AN}$  Weelden, that a diminuation of 79 milligals with regard to the North Coast of Java, has been found in the Solo Valley, while in the West of Java over a distance from the North Coast to the hills, a diminuation of about 20 milligals was found; both during investigations carried out by the geophysical survey of the "Bataafsche Petroleum Maatschappy".

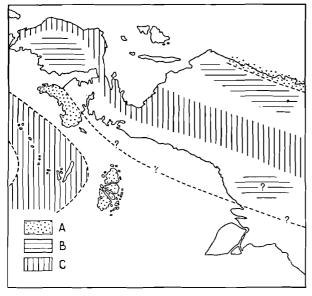


Fig. 30.

Sketch map of New Guinea and adjacent Islands showing

A. region where the Neogene has hardly been folded if at all;

B. Idiogeosynclines; C. "poly"geosynclines.

In conclusion an example from the East Coast of Borneo. In Balik Papan an anomaly of + 15 milligal which signifies a strong subsidence as compaired to the anomalies of + 59 and + 54 slightly more to the East. When we see in this connection, that a negative anomaly has been found North of Soembawa and slightly positive anomalies (+ 10 and + 13) south of Celebes southern arm, one might defend the thesis that the position of a submarine geosynclinal basin is indicated there.

New Guinea must be left entirely out of consideration because, especially along the North coast, no gravimetric data are, available to draw a comparison.

In passing I only want to point out here (see fig. 30) that a young tertiary idiogeosynclinal area is situated along the North coast of New Guinea, which can be compared with

<sup>1)</sup> See Lit. 14 pag. 778. Oil and gas wells have been found in the Sea, Malacca straits, at about 18 K.M. N.W. of "Diamantpunt". (See fig. 28).

e.g. the basin of South Sumatra, mentioned above, while the neogene folding (of which the time cannot yet be defined precisely) of the Central Snow Mountains has been much more intensive and cannot be understood without pre-supposing a very intensively overthrust structure, thus showing analogies to our "poly"geosynclinal areas (I). The occurrence of many and strong seismic centra on New Guinea makes it probable too that a net of gravimetric observations will yield interesting results.

Likewise I think it advisable not to fall into hypotheses about Halmaheira, before more and exacter geological data on the one hand and a closer net of gravimetric observations on the other are known.

On Plate III stratigraphic columns of the idiogeosynclinal regions may be found.

#### Summary and Conclusions.

Within the zone of strong negative isostatic anomalies are situated the only areas of which a very intensive miocene folding (probably during Tertiary  $f_2$ ) is known. Overthrust folds have been formed in many places in these so-called polygeosynclines. The miocene period of folding is followed by a plio-pleistocene phase of movement which is, however, characterised especially by faulting. Probably it has strengthened the negative anomalies, which must already have been weakened, to the strong negative which is still to be found (I).

Areas, which have not been folded during the Tertiary or only slightly, are characterised by weak positive anomalies. When a tertiary folding occurs, as e.g. in the S.E. of Java it corresponds with a slight sag in the gravimetric diagram (II, IIIa and IIIb).

On the ground of geological as well as gravimetrical considerations, we cannot but come to the conclusion that the deep-sea basins, some of which are characterised by strong positive isostatic anomalies, owe their origin to an upper-tertiary subsidence of areas which before were shelves, or were perhaps partly situated above the level of the sea (IIIc).

The idiogeosynclines, i.e. young tertiary basins of intensive subsidence and sedimentation, which were not-intensively folded towards the end of the Tertiary, are characterised gravimetrically by a clear decrease of the anomalies, which, generally being positive, sometimes become slightly negative here (IV).

All this clearly shows that a distinct image of the isostatic anomalies is to be seen in the entire structure and in the later geological history of the East Indian Archipelago.

By this new and exceptionally valuable source of information, which Vening Meinesz has thus added to geological knowledge — and for which indeed geologists ought to be very grateful to him — the problem of the structure and origin of the East Indian Archipelago has been put into an entirely different light, which aids considerably in the explanation of geological phenomena.

Not only have we been able to point out a direct connection between geology and deviations of isostasy in a number of restricted zones, but certain coincidences seem to indicate that the clear mutual differences in geological structure and tertiary history which we could discern for several areas, are nevertheless connected with each other and go ultimately back on one common cause. Already in 1912 Molengraaff said (lit. 8 p. 231): "..... the origin of "the deep sea basins and the elevation of the islands in the eastern part of the Archipelago may "be regarded as a simultaneous process between which a genetic connection must have existed".

If this be true, it would follow that the isostatic anomalies too must be connected with each other.

For we saw that it is very well possible

- 1. that the period of very intensive miocene folding in the strongly negative zone (I) coincides with a weaker folding (and a weaker anomaly) of the neighbouring areas (II)
- 2. that in the Neogene the idiogeosynclinal subsidence has been exceptionally strong and has far surpassed the palaeogene cycle of subsidence (see p. 156)
- 3. that the three zones mentioned here (i.e. I, II and IV) are parallel to each other over a great distance 1) (across and along Sumatra and Java) while
- 4. the recent volcanoes are preferably arranged in zones parallel to the strongly negative zones (see p. 149, 150)
- 5. that the folding of the idiogeosynclines coincides more or less (i.e. end of the Pliocene or during part of the lower Pleistocene) with the strong elevation combined with the formation of numerous faults in other areas (e.g. I) and perhaps also with the origin of the present deep-sea basins (see III c).

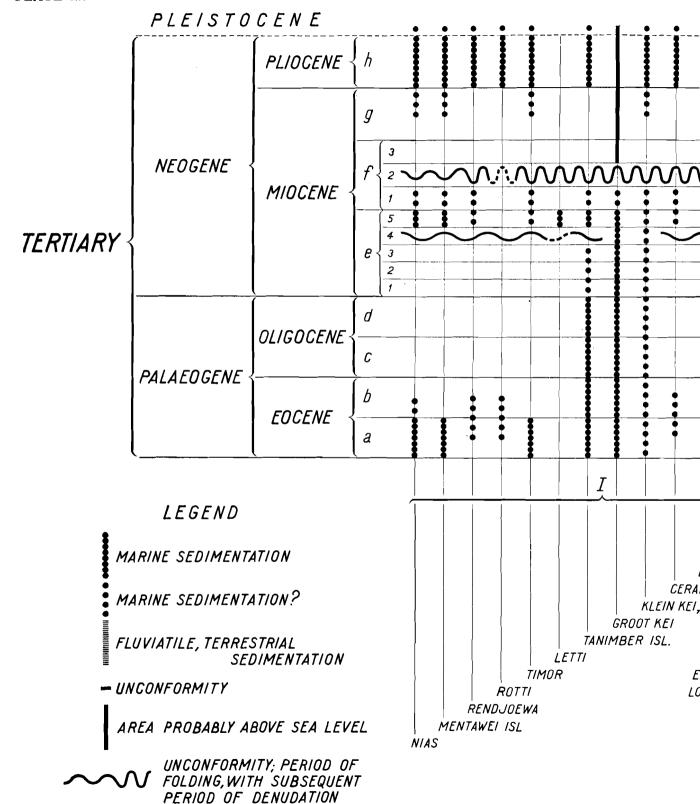
I hope that this study may form a basis for closer geophysical research and considerations (founded also on a closer net of observations) of the deeper basis — in a literal and a figurative sense — of the geological history which resulted in the present aspect of the East Indian Archipelago.

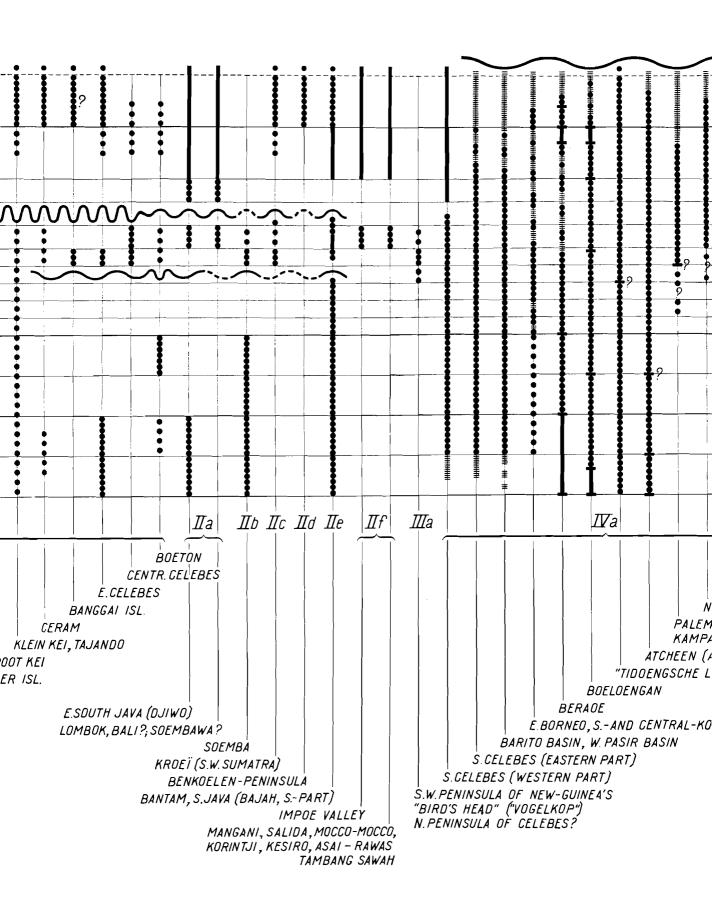
<sup>1)</sup> Hardly anything can be said about a mutual connection elsewhere, before we know more geologically as well as gravimetrically about the unknown areas, namely about Halmaheira and New-Guinea.

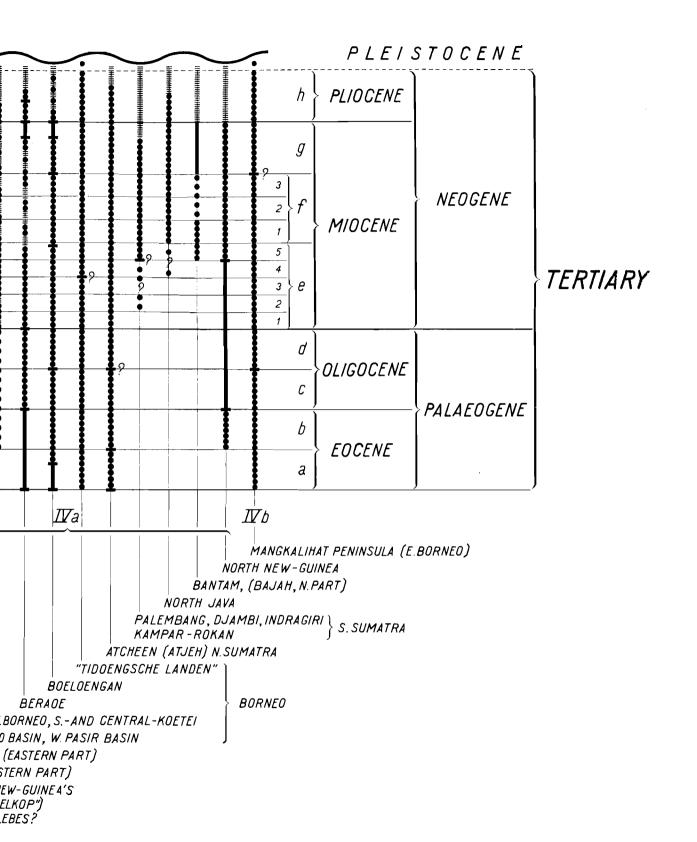
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PLATE III.









#### CHAPTER VII.

# A short Survey of Theories on the Origin of the East Indian Archipelago by J. H. F. UMBGROVE.

"These considerations are undoubtedly attractive and may contain valuable elements of truth. They may, in future, serve as working hypothesis, when we will dispose of sufficient data to make a discussion of such fundamental problems fruitfull. To day this is unfortunately not the case. For the time being all geologists in the East Indies must direct their efforts towards a much more complete knowledge of that part of the earth's crust, which is directly accessible to our observation." 1)

An entirely new source of data of great value for geology is presented by Vening Meinesz in this publication. It goes without saying that it sheds new light on the problem: How did the East Indian Archipelago originate?

For this reason it may be useful to give a short survey of the different opinions, which, have been given up to now concerning this problem, more especially as the reader may observe that in the foregoing chapters ideas are given which differ in many respects from older views.

A short survey, for it is not my intention to mention all theories in detail, to treat and to weigh them separately.

I shall only treat the opinions of Verbeek and of Molengraaff in some detail on account of the great influence they undoubtedly have had on the theories of many other authors. On the other hand many of the more than two dozen theories on the origin of the East Indian Archipelago, which have been published in the last three decennia, will only be mentioned cursorily.

The reader who feels inclined towards a more detailed study will find sufficient indications in the literature quoted to serve him as a key to a more extensive bibliography on this subject.

I have divided the material into five paragraphs. In each paragraph opinions are taken together, which in their principal trend of thought are either closely related or opposed to one another.

In the first paragraph I have thus united the theories which have the subsidence of extensive areas as main element and in § 2 those theories which consider the East Indian Archipelago as a whole to be a folded mountain chain in statu nascendi; in § 3 theories based on continental drift are brought together; in § 4 theories which especially lay stress on faulting; finally in § 5 follow some views about the conception "geosyncline".

<sup>1)</sup> L. M. R. RUTTEN. Voordrachten over de Geologie van Nederlandsch Oost-Indië 1927, p. 808, 809.

Before Verbeek had geologically explored the Eastern part of the East Indian Archipelago, during nine months of the year 1899, very few geological observations had become known of that part of the Archipelago.

Indeed, Verbeek was the first whose answer to the question how the present shape of the East Indian Archipelago had originated was supported by a body of facts from about 250 islands situated between Celebes and New Guinea 1).

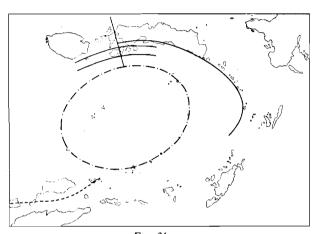


Fig. 31.

Banda sea subsidence: — faults: \_\_\_\_\_. young volcanic rocks
—— old volcanic (tertiary) rocks (after Verbeek, loc. cit. 1900).

This problem namely has a special relation to the Eastern part of the Archipelago, for the Western part — Sumatra, Java and Borneo — is even now clearly connected with the Asiatic continent by way of the shallow shelf between, while we can easily conclude from the isobaths to a similar connection between Australia and New Guinea <sup>2</sup>). Consequently the problematic part of the question chiefly concerns the eastern series of islands with the deep sea basins they enclose.

On the strength of the available data Verbeek thought that one ought to regard the Banda-sea as "an ellipse shaped basin, surrounded by a row of islands consisting mainly of old rocks

(schists, Permian, Triassic, Jurassic) although they are here and there covered by younger rocks — Cretaceous and Tertiary" (l.c. pag. 799) With the aid of the map (fig. 31) his further explanations can be easily followed; the Western "entirely collapsed" part of the circle of old sediments, the division into two parts of this strip near Kissar, the ellipse of small young volcanoes, more or less parallel to the boundary of the Banda sea etc.

I want to restrict myself to some of Verbeek's essential conclusions, and quote them: "The young tertiary sediments" says Verbeek (I.c.p. 806, 807) all have the character of formations of a comparatively shallow sea, have generally been raised under more or less steep angles, and were often cut off by faults, e.g. at the eastern side of Saleyer, bordering on a very deep sea". "The Banda sea itself originated by a big, ellipse-shaped down warping, for which the shape of the South-Eastern coast of Boeroe and Ceram, and the situation of the small islands on the eastern side, vouch".

VERBEEK thought: "that the deep basins and seas of the Moluccas are not the remainder of an older sea which was everywhere very deep, but that they originated through subsidences of the land and the bottom of the shallow seas, here and there already in the lower miocene but principally during and towards the end of the upper miocene period".

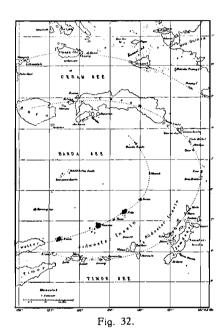
<sup>1)</sup> R. D. M. VERBEEK. Molukkenverslag. Jaarboek van het Mijnwezen in Nederl. Oost-Indië 1908. Wetenschappelijk Gedeelte en Bijlage XVII, fig. 510, kaart No. 1 en fig. 516, Bijlage XVIII.

<sup>2)</sup> See: W. E. EARLE. On the physical Structure and Arrangement of the Islands of the Indian Archipelago. Journal Royal Geograph. Society, London. Vol. 15. 1845. p. 358-367.

Verbeek had not only communicated this opinion provisionally in 1900 1) but the idea that the Banda-sea had originated through subsidence or downwarping could already be found in his publications before his visit to the Moluccas 2) (His expedition to the Moluccas induced him only to alter the details, not the principle of his idea).

Verbeek was of opinion that at the same time with the downwarping (or fault-pit) the non volcanic outer arc had been formed in consequence of a folding in the depth, which could have been caused by this downwarping (a conception analogous to ideas lately put forth by  $W_{\rm ILLIS}$  to account for the origin of the Caribbean sea; a deep sea basin which has been repeatedly compared with the Banda-sea a.o. by Peschel, Suess, Von Buch, Wichmann, Martin and Rutten 3).

For the rest. Verbeek could only arrive at the construction of those elliptical belts



Banda island arcs (after Wichmann, loc. cit. 1887)

because he looked upon the volcanoes of the Banda sea as a complex, separated from the volcanoes of the Sunda islands <sup>4</sup>), an idea which has not been followed by any of the later authors <sup>5</sup>), and which was not accepted by Wichmann either who, already before Verbeek, considered the Banda sea as a large area of subsidence, surrounded, however, as he thought by three arcs of islands <sup>6</sup>) (fig. 32).

It is evident that if one agrees with Höfer's idea 7) of an Eocene continent including Asia and Australia one must arrive at conclusions analogous to those of Wichmann and Verbeek.

In more recent times A. Holmes again launches the idea that the Banda sea had been formed by subsidence. He looks upon this area as a geosyncline in which the original floor has subsided to great depths. As a subsidiary cause competent to produce such a geosyncline he considers increase of density due to metamorphism of the underlying material. Thus the Banda sea is considered as "a region where subcontinental currents approach and throw the nearly sial-free crust into compression" 8).

<sup>1)</sup> R. D. M. VERBEEK. Voorloopig verslag over een geologische reis door het Oostelijk gedeelte van den Indische Archipel in 1899 (met een kaartje) Extra Bijvoegsel van de Javasche Courant 1900, no. 66 (Batavia, Landsdrukkerij).

<sup>2)</sup> R. D. M. VERBEEK en R. FENNEMA. Java en Madoera 1896 blz. 3 en 4, de noot 4 op blz. 4 en de kaart op Bijlage blad I.

<sup>3)</sup> L. M. R. RUTTEN. Cuba, the Antilles and the Southern Moluccas. Proceed. Kon. Acad. v Wet. Amsterdam, Vol. XXV, 1922, p. 263—274.

<sup>4)</sup> See his map in 2) and the text p. 33/34.

<sup>5)</sup> See e.g. MOLENGRAAFF's review in 1922, p. 299.

<sup>6)</sup> A. WICHMANN. Gesteine von der Insel Kisser. Samml. des Geologischen Reichs Museums in Leiden ser. 1 Bd. II, 1887, p 182—201 Tab. V (also in: Jaarboek Mijnwezen 1887. Wet. Ged. 3, p. 104—128). Containing opinions of older authors such as O. PESCHEL (1876). L. VON BUCH (1877) and O. KRUMMEL (1882).

<sup>7)</sup> H. Höfer. Das polynesische alteozäne Festland. Sitzungsberichten der kaiserl. Akad. d. Wiss. in Wien-Math. naturw. Klasse; Bd. CXVII, Abt. I, 1908.

<sup>8)</sup> A. HOLMES. Radioactivity and Earth movements. Transact. Geol. Soc. of Glascow. Vol. XVIII, p. 590 and 592, 1929.

At the same time I may mention here that some short time ago Escher 1) attempted to apply Holmes' theory to the East Indian Archipelago in relation with the isostatic anomalies found by Vening Meinesz and especially with a view to explain volcanism. Fig. 33 represents a schematic cross section through the East of Java, continued towards the South, on which Escher's representation is expressed.

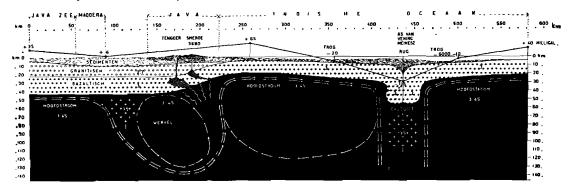


Fig. 33.

Hypothetical section through Java and the Indian Ocean (after Escher).

Hoofdstroom = Main current; Wervel = Vortex; Trog = Trough; Rug = Ridge.

Lawson 2) regards the insular arcs, which festoon the Asiatic coast not as uplifted deep

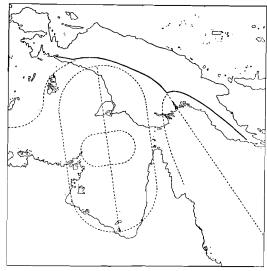


Fig. 34.

Cauldrons of Arafura sea and Carpentaria-gulf (after Heldring, loc. cit. 1909).

sea floor "but as true continental margin, which has been underthrust by the landward creep of the oceanic sima. The creep is the manifestation of the urge for isostatic equilibrium, which is upset by continental denudation. The form of the festoons arises from the geometric fact that the trace of any large thrustplane slicing the spheroid of the earth is necessarely arcuate". (l.c.p. 367, 368) According to his opinion geosynclinal seas which lie behind the arcs, and oceanic deeps which lie in front of them, are features associated with the insular arcs. Thus, he considers e.g. the Banda sea as a geosynclinal or even "epicontinental" sea. "The rise of the high central regions (Borneo and Celebes) due to removal of mass by erosion might be compensated by deep flow from under peripheral shallow seas within the arcs. If this deep flow were differential, conditioned by relative viscosity, then the heavier dunite might replace some of the

<sup>1)</sup> B. G. ESCHER. On the relation of the volcanic activity in the Netherlands East Indies and the belt of negative gravity anomalies discovered by Vening Meinesz. Proc. Kon. Acad. v. Wetenschappen Amsterdam, Vol XXXVI, p. 677—685, 1933.

<sup>2)</sup> A. C. LAWSON. Insular arcs, foredeeps and geosynclinal seas of the asiatic coast. Bull. of the Geological Society of America. Vol. 43, p. 353-382, fig. I (p. 355) 1932.

lighter crust, and so bring about the subsidence which gave these epicontinental seas their great depth" (l.c.p. 379).

Finally, I want to mention a theory in which there is question of subsidence or downwarping of extensive areas (fig. 34). O. G. Heldrig 1) namely drew two enormous faultpits, south of New Guinea, separated from each other by what he calls the "horst" of straits Torres, and separated from Verreek's Banda-sea cauldron by the "horst" of the Aroe-islands. It does not appear necessary to go further into this theory, which is lacking a sound basis as has been pointed out by Rutten 2).

§ 2.

During his explorations on Timor Molengraaff 3) found amongst others that in the district of Amanatan the parallel ridges of the Amanoeban-mountain chain, which is mainly composed of Jurassic strata striking E 10 N — W. 10 S (a direction differing about 12° from the general trend of the coast line) follow each other abruptly abutting against the coast and terminating in high cliffs. The sea deepens suddenly all along this coast and no trace of islands or shoals are found which might be regarded as the submarine continuation of those ridges. All observations made along this coast give support to the opinion that the island terminates here against a fault facing the Timor-sea (l.c.p. 230, 231).

Molengraaff writes further: "Not only Timor, however, is thus bordered at both sides by deep sea-basins, but it is a coincidence which holds good for the majority, if not for all of the islands of the eastern portion of the archipelago, consequently, the origin of the deep sea-basins and the elevation of the islands in the eastern portion of the archipelago may be regarded as a simultaneous process between which a genetic connection must have existed".

"The genesis of adjoining sunken and tilted blocks must be the result of one and the same crustal movement, which in my opinion would be the cause of a process of folding at great depths".

"If the question were raised as to what might be seen at the earth's surface if an area were folded by crustal movement at a certain depth, I should be inclined to reply that its appearance would be similar to what obtains at present in the eastern portion of the Indian archipelago 4). It is a well known fact that the folding of rock-strata is only possible under high pressure; it may therefore be inferred that folding can only originate at certain depths below the earth's surface. At the surface, in the zone of fracture, where the rocks cannot be plicated, the phenomena of deeply seated thrust and folding would be indicated by the presence of "graben" and "horsten", the former corresponding to the troughs, the latter to the saddles of the deeply seated folds. Generally speaking every range of tilted blocks, or islands in our case, as well as every range of sunken blocks, or deep sea basins in our case, must indicate the position and the trend of the major folds, which are in mode of formation at a certain depth; thus the character of the deeply seated folds would be found reflected in the surface topography".

<sup>1)</sup> O. G. HELDRING. De Zuidkust van Nieuw Guinea. Jaarboek Mijnwezen. Wetenschappelijk Gedeelte 1909, p. 85–186, Pl. VI.

<sup>2)</sup> See RUTTEN. Voordrachten l.c. p. 793.

<sup>3)</sup> G. A. F. MOLENGRAAFF. On recent crustal movements in the island of Timor and their bearing on the geological history of the East-Indian archipelago. Proceedings Kon. Acad. v. Wetensch. Amsterdam. Vol. XV. 1912.

<sup>4) &</sup>quot;ABENDANON has arrived at a somewhat similar conclusion, in his analysis of the topography of the island of Celebes. E. C. ABENDANON. Celebes en Halmaheira. Tijdschr. Kon. Ned. Aardrijksk. Genootschap 2, XXVII, p. 1149, 1910."

"But then one has to take into account also the submarine topography." (l.c.p. 231, 232.) Also in 1922 Molengraaff 1) regards: "the groups of islands in the East Indian Archipelago as the anticlinal belts, and the series of deep sea basins as the synclinal girdle of the large folds of a folded mountain ridge which is still in full development" (l.c.p. 289).

Molengramer thus arrives at a theory which differs in many respects from that of Verbeek. In trying to fix the trend of these supposed large anticlinal and synclinal belts, the submarine morphology plays an important part, and the constructions cannot but be subjective and groping, especially in areas where the depth figures were then scarce (cf. the new bathymetric chart of the Snellius expedition Pl. V).

In his publication of 1922 MOLENGRAAFF explained exhaustively how he imagines the construction of this supposed folded mountain chain in statu nascendi, situated between the Asiatic continent (with the Sunda shelf) and the Australian Continent (with the Sahul shelf).

It is of fundamental importance that Molengramer states as his opinion that the youngest mountain building (orogenetic) movements, the expressions of which seem to differ so radically from those of the pre-pliocene movements in reality have the same character and that the difference lies only in the "tectonic level" on which we can study the results of these movements 2) (see also the quotation from Rutten, p. 147).

This original opinion of Molengraaff has been propagated in numerous publications and has been worked out by H. A. Brouwer. The trend of the geanticlines as imagined by Brouwer is represented in fig. 35, (after fig. 1 from his publication in 1925 ³) where a survey of his views may be found, which, moreover were briefly and clearly summarised by Rutten) ‡). Following Argand 5) he compares the Archipelago in its entirety with the Alps in their mesozoic embryonal stage. Of the geanticlines, which, according to Brouwer could execute a movement with a considerable horizontal component, the so-called" axes" are indicated by lines on this map. According to Stille 6), however, the proofs for such a conclusion are lacking, and the phenomena may also be explained in another way, viz. by supposing vertical epirogenetic movements and not horizontal movements.

These lines partly indicate the trend of the present shape of the islands, such as the line which has been drawn across Soemba via Timor, Tanimber, Kei islands and Ceram till Boeroe, or partly they follow supposed submarine ridges (see the bathymetric chart of the Snellius expedition Pl. V) such as the eastern part of the inner Banda arc; they run across regions with a mutually very different structure and tertiary history, thus e.g. across the four arms of Celebes; or they follow the morphological highest points of an island such as the Barisan in Sumatra (i.e. across volcanic tops, Tertiary ad pre-Tertiary) or they connect a folded tertiary area such as North Halmaheira with the Pelew islands where the line runs through the sea over a distance of some 900 k.m. and runs straight across a deep sea basin (see the new bathymetric chart of the Snellius expedition Pl. V).

<sup>1)</sup> G. A. F. MOLENGRAAFF. Geologie in: De zeeën van Nederlandsch Oost Indië, 1922.

<sup>2)</sup> L. RUTTEN. Voordrachten 1927. p. 751.

<sup>3)</sup> H. A. BROUWER. The Geology of the Netherlands East Indies 1925. ed. The Macmillan Company, New York.

<sup>4)</sup> L. RUTTEN. Voordrachten 1927. p. 751-758.

<sup>5)</sup> E. ARGAND. Sur l'arc des Alpes occidentales. Eclog. Geol. Helv. XIV, 1916, p. 179-182.

<sup>6)</sup> H. STILLE. Die angebliche junge Vorwärtsbewegung im Timor-Ceram-Bogen. Nachr. Kön. Ges. der Wissensch. in Göttingen 1920, p. 174–180.

See also: H. STILLE. Alte u. junge Saumtiefen, ibid. 1919, p. 237-372.

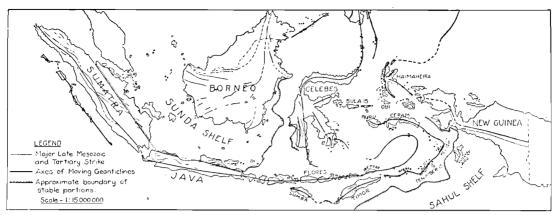


Fig. 35. Tectonic map of the East Indian Archipelago (after Brouwer, loc. cit. 1925).

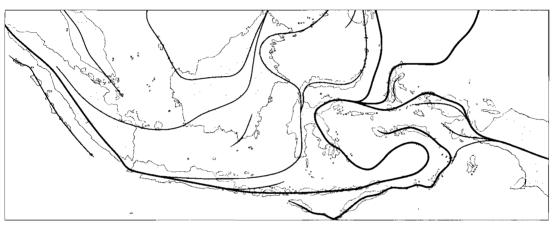


Fig. 36. Tectonic map of the East Indian Archipelago (after R. Staub, loc. cit. 1928).

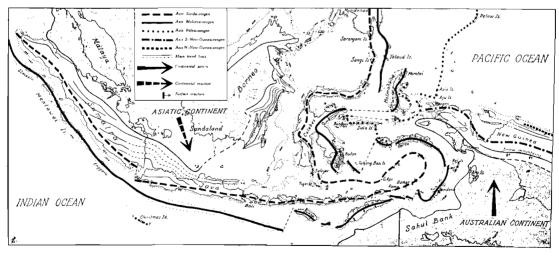


Fig. 37. Tectonic map of the East Indian Archipelago (after Smit Sibinga, loc. cit. 1933).

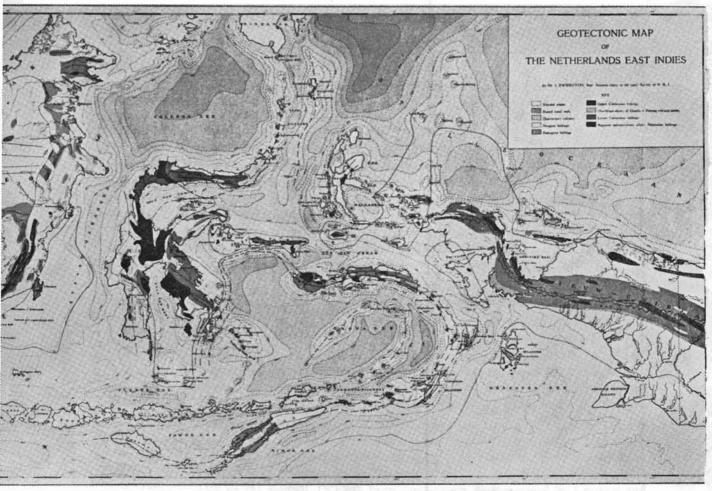
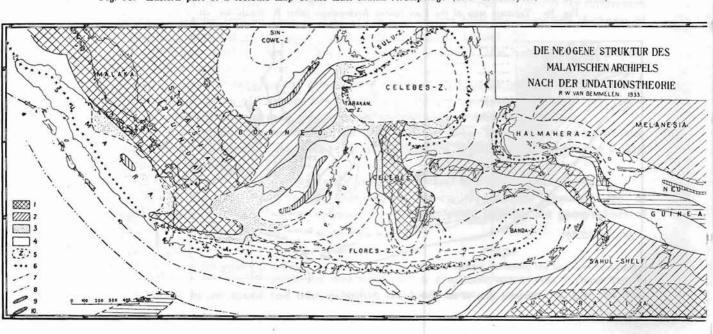


Fig. 38. Eastern part of a tectonic map of the East Indian Archipelago (after Zwierzycki, loc. cit. 1929).



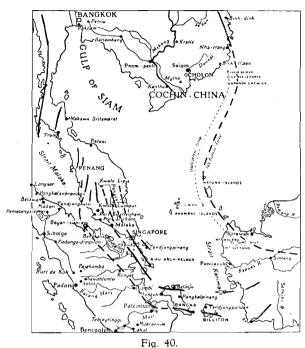
- Kratogene Gebiete ohne transgressives Neogen.
   Semikratogene Gebiete mit transgressiven Neogen, doch nicht oder noch nicht von den neogenen Undationszyklen betroffen.

- Schwellengebiete (Übergangsgebiete zwischen Kratogen und Orogen).
   Orogene Gebiete.
   Orogene Zentren, von denen im Neogen Undationszyklen ausgegangen sind.

- Vulkanische Mesoundationen (vulkanische Innenbögen).
   Nichtvulkanische Mesoundationen (nichtvulkanische Auszenbögen).
   Neuer nichtvulkanischer Auszenbögen in statu nascendi (Christmasinselbögen).
- 9. Mesoundatorische Mittelschwellen der neogenen, mesosynklinalen Sedimentationsbecken.
- 10. Geoundatorische zirkumaustralische Mittelschwelle,

Fig. 39. Tectonic map of the East Indian Archipelago in the Neogene (after Van Bemmelen, loc. cit. 1933).

In order to fix our ideas, it may be useful to draw such lines across islands which, for some reason or other one thinks belong together, and it goes without saying that different



Map showing "the submarine tecto-volcanic line Borneo-Annam" (after van Es, loc. cit. 1926).

authors do not make identical suppositions concerning the same subject. We may therefore expect a priori that Staub's 1) tectonic map (fig. 36) looks different from Brouwer's (fig. 35), that Schürmann's 2) picture is again different (fig. 50) and that Smit Sibinga 3) has designed a picture which again differs from this latter (fig. 37), while Zwierzycki's 4) "geotectonic map" (fig 38) has a different aspect from all the rest and finally the same may be said of a map recently published by Van Bemmelen 5) (fig. 39).

That in constructing such "tectonic lines" one does not shrink from speculations, may also be seen from the following example (fig. 40).

Van Es <sup>6</sup>) supposes namely that in South Western Borneo the older mesozoic formations have, in general, a North-Westerly to South-Eastern trend and that, consequently this trend is continued across the Natoena islands and may be refound in the mountains

along the Eastern coast of Annam. Parallel to this mesozoic trend in Borneo, we find according to Van Es the expression of very young volcanism which is not yet extinct. The prolongation of this belt of volcanoes would then be visible in the island of Midai, S. of Natoena, while in Indo-China this line would have been exposed in the recent eruption of l'ile des Cendres, near the island of Cécir de Mer.

So these data have been connected by two elegantly bent lines, one tectonic and one volcanic of about 1000 k.m. long, running through the sea over a distance of 500 k.m. apparently without expressing themselves.

<sup>1)</sup> R. STAUB. Der Bewegungsmechanismus der Erde. Ed. Borntraeger 1928, p. 71, fig. 21a.

<sup>2)</sup> H. M. E. SCHURMANN. Über die Neogene Geosynclinale von Süd-Sumatra etc. Geol. Rundschau, Bd. 14, p. 242, fig. 1.

<sup>&</sup>lt;sup>3</sup>) G. L. SMIT SIBINGA. The Malay double (triple) orogen. Proceedings d. Kon. Acad. v. Wet. Amsterdam, Voi. XXXVI, 1933.

<sup>4)</sup> J. ZWIERZYCKI. Toelichting bij de geotektonische kaart van Nederlandsch Indië 1:500.000. Jaarb. Mijnwezen Verh. 1929.

<sup>5)</sup> R. W. VAN BEMMELEN. Die neogene Struktur des Malayischen Archipels nach der Undationstheorie, Proc. Kon. Acad. v. Wet. Amsterdam. Vol. XXXVI, 1933, p. 887—896, fig. 2.

<sup>&</sup>lt;sup>6</sup>) L. J. C. VAN Es. Relations between the new volcano of the ile des Cendres (Annam) and extinct volcanoes in Borneo. Bulletin Volcanologique, Napoli 1925 (ed. 1926).

It is almost unnecessary to mention that Krol's 1) hypothesis which supposed all geological formations in the entire East Indian Archipelago to be characterised by a certain and constant strike, and, in consequence, that they could be determined by strike measurements could be easily refuted by Krekeler 2) on the ground of some concrete examples.

§ 3.

In his original theory of folding Molexgraaff presupposes centrifugal pressures originating in the Banda Basin 3). About this he says himself 4):

"Hobbs 5) pointed out the mechanical improbability of the occurrence of such centrifugal pressures in arcuate folded mountain chains with centrifugally directed overthrusts, and showed that it is mechanically more feasable to suppose that the pressure does not originate in the folding mountain range but rather at some depth, from the surrounding region, i.e. from the foreland. We would then be dealing not with centrifugal overthrusts but which centripetal underthrusts".

Such underthrusts might e.g. be caused by a North-Western movement of the Australian continent as was supposed by Wegener. Before going into this theory any farther, however, I must mention that, formerly Ed Suess 6) did not suppose the continuation of the islands of Boeroe and Ceram to be arc-shaped towards Timor, but to run easterly towards New Guinea. We meet again with this idea not only with Supan 7) (fig. 41) but also in the view given by Gregory 8) ten years ago.



Fig. 41.
Island arcs of the West Pacific (after Supan, loc. cit. 1916).

According to Wegener's theory on continental drift the Lesser Sunda islands and the Southern Moluccas formed originally two East-Westerly extended series, which had their continuation in the Bismarck Archipelago. By the North-Western drift of the Australian block

<sup>1)</sup> L. H. Krol. De mesozoische plooiïngen op Borneo en omgeving en hunne waarde voor het karteeren van fossiellooze gebieden. De Mijningenieur 11, p. 68–92, 1930.

<sup>&</sup>lt;sup>2</sup>) F. KREKELER. Critische beschouwingen over een nieuwe door ing. L. H. Krol gepropageerde kaarteeringsmethode voor de mesozoische formaties in den Nederl. Ind. Archipel en omgeving. De Mijningenieur No. 11, p. 206—211. 1932.

<sup>3)</sup> See also B. WILLIS' theory, following below.

<sup>4)</sup> G. A. F. MOLENGRAAFF l.c. cit. 1922, p. 300.

<sup>5)</sup> W. H. HOBBS. Mechanics of the formation of arcuate mountains. Journ. of Geology XXII, p. 31, 1914. See also: W. H. HOBBS. The unstable middle section of the island arcs. Verh. Geol. Mijnb. Gen. v. Ned. en Kol., Geol. Ser. Dl. VIII, p. 219—261, 1925.

<sup>6)</sup> ED. SUESS. Das Antlitz der Erde (English Edition) 1908. Vol. III, p. 243.

<sup>7)</sup> A. SUPAN. Grundzüge der Physische Erdkunde 1916, pag. 783, fig. 265.

<sup>8)</sup> J. W. GREGORY. The Banda arc. The Geographical Journal 62, p. 20-32, 1923.

with New-Guinea attached to it, the insular arcs of the East Indian Archipelago are supposed to have been rolled up into spirals, schematically represented in fig. 42 <sup>1</sup>) Wegener's theory has been acclaimed by numerous explorers of the East Indian Archipelago <sup>2</sup>).



Fig. 42. Island arcs deformed by advancing New Guinea (after Wegener, loc. cit. 1922).

SMIT SIBINGA tried to extend it by applying it more particularly to the shape of the island arcs of the Moluccas, which he supposes to have extended via Celebes to the Philippines, and to the situation of the supposed transverse faults diverging in the direction of the Banda sea  $^3$ ) (see also fig. 37).

Wing Easton 4) has even gone so far as to suppose that the Malay Archipelago forms only a part of a big

migration which originated in Antarctica: "of the already much crumbled part of that continent, situated between the Ross Barrier and Grahamland, blocks came off successively, consisting mainly of pieces of shelf border and moved away. roughly speaking, in a North Westerly direction". "Many Eastern islands of the Archipelago have been overtaken and carried along by Australia which was then coming from Wilkesland".

Gerth 5) mentioned difficulties of a palaeogeographical and climatological nature against the application of Wegener's theory in the Permain, while Kuenen 6) brought forward some six objections which are partly of a geological and partly of a morphological nature, based on the new bathymetric chart of the Snellius expedition.

Amongst others Kuenen points to the uniformity of the orogenetic belt of the East Indies opposite and beyond the Australian block. This proves, according to his opinion, the active element to be Asia and proves at the same time the ocean bottom and Australia to react in the same manner and degree. The direct continuation of the Timor trough, according to Wegener the scar where Australia was grafted onto the arcs, into the Java trough that lies beyond this mass, and the several ridges connecting the Australian mass directly with the Asiatic elements, are so many morphological features opposing a recent joining of the two parts. The identity of the mesozoic sediments of two parts of the Australian block (Misool and northern New Guinea) with two others of the arcs (Ceram and the Soela Islands respectively) froms a crossed link between the East Indies and Australia.

In their treatises on "isthmian links" and landbridges  $W_{\rm ILLIS}$  7) and  $S_{\rm CHUCHERT}$  8) entirely reject the theory of continental drift. They suppose, on the contrary, that the continents

<sup>1)</sup> A. WEGENER. Die Entstehung der Kontinente und Ozeanen 3e Aufl. 1922. p. 47, 47, fig. 12 and 13.

<sup>2)</sup> See e.g. G. A. F. MOLENGRAAFF. l.c. 1922, p. 300, 301.

<sup>&</sup>lt;sup>3)</sup> G. L. SMIT SIBINGA. Wegener's theorie en het ontstaan van den Oostelijken O. I. Archipel. Tijdschrift Kon. Nederl. Aardr. Genootschap DI. XLIV, 1927, p. 581—598, fig. (p. 585).

<sup>4)</sup> H. WING EASTON. Wegener's theorie toegepast op de Maleische Archipel. Versl. Geol. Sectie van het Geol. Mijnb. Genootschap in Nederland, Deel III, p. 25—26, 1921.

<sup>&</sup>lt;sup>5</sup>) H. GERTH. Die Korallenfauna des Perms von Timor und die Permische Vereisung. Leidsche Geologische Mededeelingen, Deel 11, p. 7-14, pl. 4, 1926

<sup>6)</sup> Ph. H. Kufnen. De Beweging van Australië ten opzichte van Nederlandsch Indië. Vakblad voor Biologen. Jaarg. 14, No. 12, 1933.

<sup>7)</sup> B. WILLIS. Isthmian Links. Bulletin of the Geol. Society of America. Vol. 43, p. 917-952, Pl. 28, 1932.

<sup>8)</sup> CH, SCHUCHERT, Gondwana Land Bridges. Bull. of the Geol. Society of America. Vol. 43, p. 875-916, Pl. 24, 1932.

have been constant in their essential shape and situation. WILLIS tries to make clear how narrow connections between continents, so called isthmi, can originate by means of the isthmus which connects North and South America and the insular arc of the Antilles. According to his opinion "the energy of the dynamic Caribbean has caused uptrusions of plutonic masses, establishment of numerous volcanic centers along arcs of its framework, overthrusting and folding

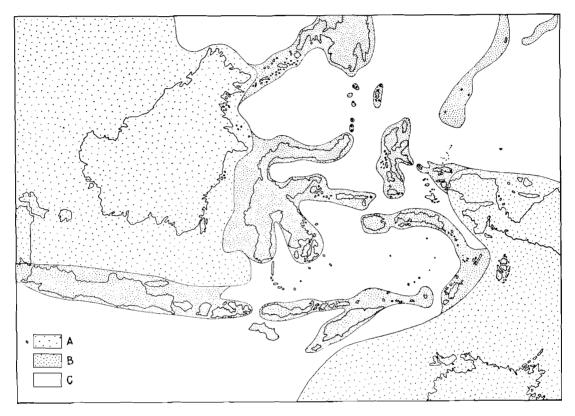


Fig. 43.

Map of the East Indian Isthmi; A. permament continental masses; B. temporary isthmian connection;

C. oceanic basins (after Willis, loc. cit 1932).

of marginal zones, and oscillations of level, both up and down, to the amount of thousands of feet" (loc. cit. p. 929). In the same way he also constructed isthmian links in the East Indian Archipelago, and of these he says: "Again we look to the activity of the deeps to establish the links by raising their margins" (l. c. p. 940).

A further argumentation for Willis' construction, which we reproduce here (fig. 43) will, however, be looked for in vain in his treatise.

§ 4.

Before we proceed to mention some theories concerning the origin of the East Indian Archipelago in which extensive fault-structures play an important part, some general remarks about the hypothetical construction of faults in the East Indian Archipelago must precede.

Besides faults which have been constructed on the ground of clearly mapped out geological structures, other reasons led to the conclusion about faults, such as e.g. the existence of volcanoes or small craters whose arrangement and transformation have generally been considered as connected with pre-existing fissures in the substratum.

According to  $V_{\text{ERBEEK}}$  and  $F_{\text{ENNEMA}}$  the direction of the principal fissure on Java is parallel to the longitudinal axis of the island 1) (fig. 44).

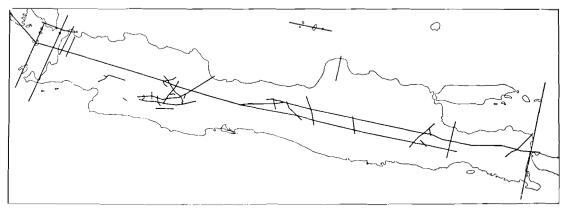


Fig. 44. Faults on Java and in Sunda Straits (after Verbeek, loc. cit. 1896).

They drew, moreover, numerous transverse fissures which connect some volcanoes in a rather arbitrary manner. Now the volcanoes can easily be connected by other lines and, besides, very often no crater occurs over long distances of the lines. On these reasons  $T_{\text{AVERNE}}$  2) rejects  $V_{\text{ERBEEK}}$ 's longitudinal fissures and is of opinion that, with a few exceptions  $V_{\text{ERBEEK}}$ 's transverse fissures are of no value either. On the other hand, from the morphology of several volcanoes, viewed separately, he concludes to fissure trends which, in general run diagonally with regard to the trend of the island.

In this way two intersecting fissures, N.W. - SE and SW - NE, could be deduced for two Javanese volcanoes, the Goentoer and the Lamongan. As a matter of fact, these two volcanoes formerly belonged to the most active centres of Java, and violent eruptions may also be expected from them in the future.

Fig. 45 shows a tectonic speculation based on the distribution of volcanoes in the northern Moluccas 3).

As faults with a considerable displacement could only be proved very seldom and with great difficulty on the basis of imperative and detailed geological mapping — which, for the rest, is not to be wondered at in a tropical region with its dense vegetation and thick weathering deposits — it is remarkable that transverse shift faults have been drawn between many islands. These supposed transverse shift faults are partly based on the lateral displacement of the geanticlinal axis (see fig. 37 and 50). They correspond with deeper straits as e.g. between the islands of the Timor-Boeroe arc, and, as a matter of course, fit in with the

<sup>1)</sup> R. D. M. VERBEEK and R. FENNEMA. Geologische beschrijving van Java en Madoera. Atlas Pl. II. 1896.

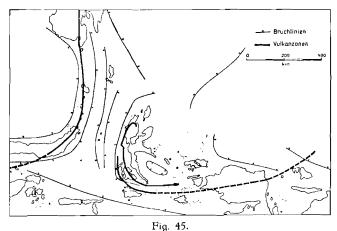
<sup>2)</sup> N. J. M. TAVERNE. Vulkaanstudiën op Java. Vulkanologische Mededeelingen, Nr. 7, 1926, p. 123-125.

E. GOGARTEN. Die Vulkane der nördlichen Molukken. Zeitschrift f. Vulkanologie. Ergänzungsband II, Tafel IV, fig. 1, (See also fig. 2, 3 and 4), 1918.

theories given by Molengraaff, Smit Sibinga, Hobbs and Brouwer; the latter especially dedicated exhaustive treatises to this subject 1).

In some cases the arguments are based on the geological structures on either side of the straits.

Thus e.g. WANNER 2) believes on geological grounds that, with respect to Ceram, Boeroe has been displaced some tens of kilometres along a transverse shift fault; (see fig. 50) the



Tectonic map of the northern Moluccas (after Gogarten, loc cit. 1918).

southern part of the 5000 m deep strait of Manipa is said to owe its origin to this fact.

A number of authors suppose a shift fault, or some parallel shift faults to exist between Java and Sumatra, through the straits of Sunda. This is, of course, very wel conceivable, but a clinching geological proof and the eventual amount of the displacement can hardly been given as long as the adjacent areas of Java cannot, on the ground of exact detailed mapping, be compared with the geological maps of Sumatra which appeared recently.

VERBEEK constructs the supposed shift fault between Java and Sumatra by joining some volcanoes by lines, and in the group of theories of bended geanticlines the straits of Sunda is a place where the arc was broken as a result of over bending.

There would be no reason at all to suppose that shift faults exist in the straits between Java, Bali, Lombok, etc. Neither the geology which is badly known, but which seems to show points of resemblance between the islands on either side of the straits, nor the depth of the straits which between Java and Bali is only  $\pm$  50 m, between Bali and Lombok 200-500 m, between Lombok and Soembawa and between Soembawa and Flores less than 200 m, nor the morphology of this series of islands which, as it were forms a continuation of S. Java, could support such a fault construction.

Moreover, Weber  $^3$ ) already pointed to the severe scouring effect which the strong seacurrents have in the straits between these islands.

Also in the straits of Manipa e.g. the scouring effect was made probable to a depth of 900 m, "seeing that on two soundings the lead stuck hard and brought up no bottom sample, on the third only some gravel and coarse sand" 4).

The probability has also been demonstrated that the straits of the Thousand Islands in the Java sea owe their origin to the scouring effect of sea currents 5).

<sup>1)</sup> H. A. BROUWER. Fractures and Faults near the surface of moving geanticlines. Proceed. Kon. Acad. v. Wet. Amsterdam. Vol. XXIII, 1920. See also STILLE, loc. cit. 1920; See further MOLENGRAAFF loc. cit. 1922, p. 289, 290, 291, 296, 297 and 298; See also SMIT SIBINGA l.c. 1927 and his map fig. 37.
 J. WANNER. Zur Tektonik der Molukken. Geol. Rundschau, Bd. XII, 1921, p. 155—165.

MAX WEBER. Siboga Expedition. Monograph I. Introduction et description de l'Expedition, 1902, p. 20, 21. G. F. TYDEMAN. Siboga Expeditie. Monograph III. Hydrographic Results 1903, p. 6, see also p. 85–86.

J. H. F. UMBGROVE. De koraalriffen der Duizendeilanden (Java Zee), with summary in English. Wetenschappelijke Mededeelingen no. 12, Pl. I, 1929. (Dienst van den Mijnbouw in Nederl. Indië).

The greatest depth occurs there between the islands Pajoeng and Tidoeng (more than 90 m) whereas in places where the effect of the sea currents is only small, e.g. in the adjacent region, the depth of the Java sea is only 25 — 30 m. The origin of these straits dates to all probability only from the end of the Pleistocene and the force of these currents is considerably less than that of the currents which run through the straits of Bali, Lombok, etc. where, mereover the currents may have exerted their scouring effect for a longer time.

It is especially Gardiner 1) who ascribed a far reaching influence to the erosive action of the sea currents. He even goes so far as to say: "There seems to be a strong case for the separation of islands, particularly of the line from Sumatra to Timor or Timor Laut, having been occasioned, not by subsidence but my marine actions in progress since the Pliocene period" (loc. cit. p. 320).

Let us now, however, return to the fault-structures. Two authors, viz.  $V_{\rm OLZ}$  and  $E_{\rm LBERT}$  have drawn lines in an exceedingly curious way through the East Indian Archipelago, which are said to represent faults.

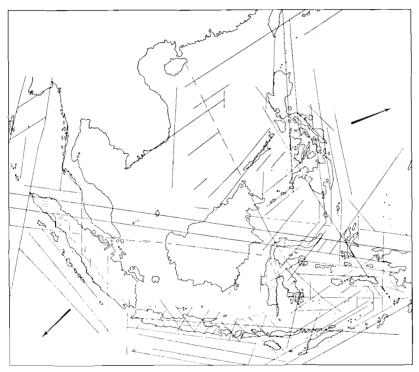


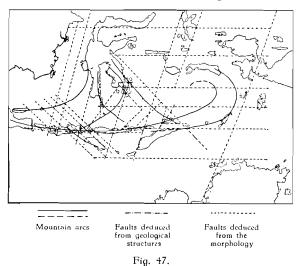
Fig. 46. Geotectonic map of the East Indies (after Volz, loc. cit. 1912).

 $V_{\rm OLZ}$  <sup>2</sup>) specially draws the attention to the fact that in Sumatra the pre-tertiary substratum is visible up to 200 m above the level of the sea and that this height gradually diminishes

<sup>1)</sup> J. S. GARDINER. The Indian Ocean The Geographical Journal 1906, p. 313-471.

<sup>2)</sup> W. Volz. Der Malaiische Archipel, sein Bau und Zusammenhang mit Asien. Sitzungsber. der Physikalischmedizinischen Societät in Erlangen. Bd. 44, p. 178–204, 1912.

towards the South. In Central Java the pre-Tertiary is only just visible and on the Eastern group of islands it is entirely lacking. On the other hand, old sediments reappear in the group of islands from Soemba via Timor and Ceram to Eastern Celebes. On the ground of such considerations he comes to the conclusion that the occurrence of Tertiary is joined to subsided blocks, and besides that the folding of the Tertiary is only a secondary phenomenon and



Geotectonic map of the eastern part of the East Indian Archipelago (after Elbert, loc. cit. 1912; from L. Rutten "Voordrachten" 1927 pag. 525, fig. 155).

subordinate to an enormous network of faults and sunken blocks, which in their turn are supposed to have been caused by "Zerrung infolge Versinkens des Pazifischen und Indischen Ozeans". Fig. 46 represents his idea. In fig. 47 one finds a tectonic map, designed by his congenial mind ELBERT 1). RUTTEN 2) says that this map is the worst example of the craze for drawing lines which can be found in the literature about the East Indian Archipelago, and he goes on: "I remember one of my collegues once asking me in the Indies whether the beautiful lines in Elbert's map represented the routes of the Royal Packet Navigation Company" (l. c. p. 526).

In accordance with ELBERT's wish, the investigator of the collection of East

Indian fishes, which he brought with him, tried to find an answer to the question how the East Indian Archipelago originated, exclusively with the aid of ichthyological data. The geological considerations thus given by Popta 3) give such striking evidence of amateurism as regards geology that we need not further mention them.

## § 5.

On the evidence of faunistic resemblances between the palaeozoic and mesozoic sediments of the East Indian Archipelago and several finding places in Europe and Asia, situated within the area of the Tethys geosyncline,  $H_{\rm AUG}^{-4}$ ) thought that he could follow this geosyncline down to the East Indian Archipelago where, according to his opinion it meets the so-called circumpacific geosyncline (fig. 48).

If one accepts this theory — cum grano salis — it still has to be admitted, that not much is known about the palaeozoic and mesozoic history of this part of the Tethys. It is not only the restriction and the comparatively small number of outcrops which must be blamed for

<sup>1)</sup> J. Elbert. Die Sunda Expedition. Bd. II, 1912.

<sup>&</sup>lt;sup>2</sup>) L RUTTEN, Voordrachten over de Geologie van Nederl. Oost Indië, 1927.

<sup>3)</sup> C. M. L. POPTA, Het ontstaan van den Oost Indischen Archipel. Ed. Brill, Leiden 1925; see also: C. M. L. POPTA. Die Verbreitung der Fische in dem Gebiete des heutigen malayischen Archipels im Hinblick auf den ehemaligen Zusammenhang zwischen Asien en Australiën. Zoologischer Anzeiger. Bd. LXVI, p. 287—298, 1926.

<sup>4)</sup> E. HAUG. Traité de Geologie 1907, p. 1563, fig. 431.

this, but especially the large areas between the islands which are flooded by the sea and so are inaccessible to direct geological observations.

In 1900 VERBEEK 1) came to the conclusion "that we shall never be able to form an exact idea how this region" (i.e. the Eastern part of the East Indian Archipelago) "looked before

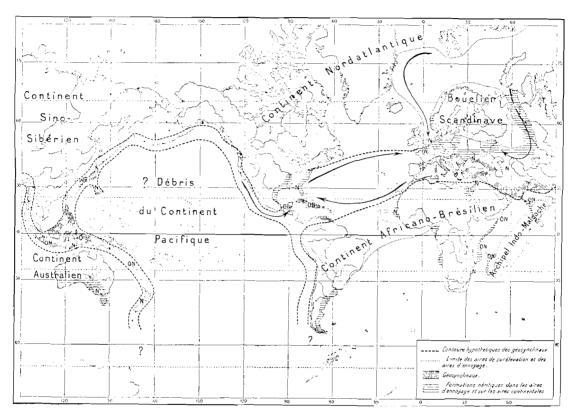


Fig. 48.
Palaeogeographic map of the Earth in the Lower-Tertiary. Vertical lines: geosynclines (after Haug, loc. cit. 1907).

the great downwarping in the seas of Banda and Halmaheira. For this the remainder of the land, especially of the sedimentary strata is too small; vast formations: Permian, Triassic, Jurassic and Cretaceous may have disappeared into the Banda sea. The fact that jurassic and cretaceous fossils have been found on Taliabo and Mangoli indicates that mesozoic strata existed in the area north of Ceram; and as Triassic and Jurassic also occur on Babar, Timor, Roti and Savoe, these formations to all probability also existed in the area where the Banda

<sup>1)</sup> R. D. M. VERBEEK, Voorloopig verslag over eene Geologische Reis door het oostelijk gedeelte van den Indischen Archipel in 1899. Extra Bijvoegsel der Javasche Courant 1900, Nr. 66.

sea is situated now. But it will probably always remain impossible to prove this more conclusively or to give an answer to the question whether it was a comparatively low region or a high alpine mountain range which disappeared in the depth here!"

This opinion of Verbeek is of course entirely correct.  $^{1}$ ) It is true that  $W_{ANNER}$   $^{2}$ ) pointed out that the facies of the mesozoic sediments of the East Indian Archipelago in the East

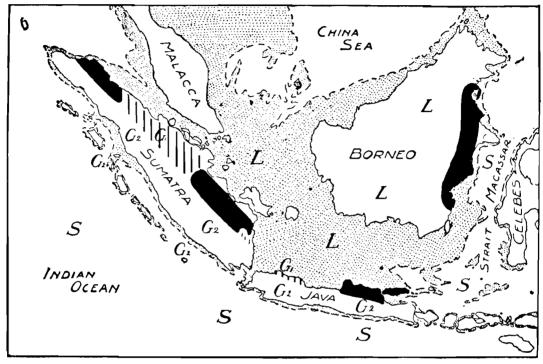


Fig. 49. Neogene geosynclines (after Molengraaff, loc. cit. 1920). Solid-black: Oilfields in neogene geosynclinal deposits. Vertical lines: Neogene geosynclinal deposits, in which the occurrence of petroleum has not yet been established. Dots: Sunda shelf.

generally point to sedimentation in a deeper sea than in the West (but sediments with "deeper" facies have since also been met with in the West 3), but the fact that e.g. upper triassic rocks have been found on certain islands of the Moluccas does not give us the certainty that the trend of a triassic geosyncline is indicated exactly by those islands — even if we do not take into

<sup>1)</sup> See also K. MARTIN. Zur Frage nach der Entstehung des Ost- und West Indischen Archipels. Geograph. Zeitschrift II, 1896. p. 361-375; K. MARTIN. Mesozoisches Land und Meer im Indischen Archipel. N. Jahrb. für Mineral. etc. 1907; K. MARTIN. Ein Zweiter Beitrag zur Frage nach der Entstehung des Ost-Indischen Archipels. Geograph. Zeitschrift 13, 1907.

<sup>&</sup>lt;sup>2</sup>) J. WANNER. Die Malaiische geosynklinale im Mesozoikum. Verh. Geol. Mijnb. Genootschap voor Ned. en Kol. Geol. Serie Deel VIII, p. 569–600, 1925.

<sup>3)</sup> See: De Mijningenieur 1930, p. 74-75,

account the fact that we know little about the stratigraphy and thickness of these sediments; for the rest Smit Sibinga considers this possibility to be a certainty 1).

In this latter case, and also in several places of the literature about the Tertiary, the name "geosyncline" is used for a relatively narrow zone situated within the boundaries of  $H_{AUG}$ 's Tethys.

The tertiary so-called geosynclines are relatively narrow basins, where, during the Tertiary enormously thick sediment layers accumulated. The sediments consist partly of volcanic efflata, but for a great part of material which originated by erosion and denudation from adjacent regions situated above the level of the sea.

Thus MOLENGRAMET 1) showed that the tertiary geosynclines of Sumtra, Java and Borneo (G 1 on fig. 49), skirt an extensive tertiary continental area, the so-called Sundaland (L on fig. 49), while moreover parts of Western Sumatra and Southern Java (G 2 on fig. 49) were raised above the level of the sea, during the time that the subsidence in the geosynclines was still going on, and so fell victims to the erosion as well.

A somewhat different opinion is held by Schürmann 2) who indicates a direct connection between the geosynclinal regions of Sumatra and Borneo (fig. 50).

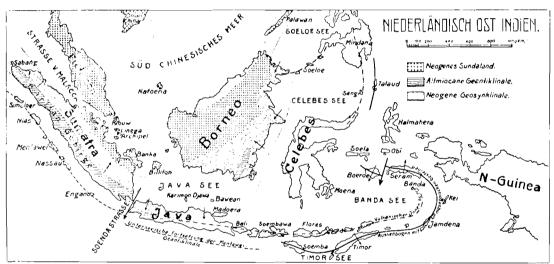


Fig 50, Geotectonic map of the East Indies (after Schürmann, loc. cit. 1923); dotted: neogene geosynclines.

I need not say more about these tertiary geosynclines because I have gone into them more in detail elsewhere in this treatise (Chapter VI, sub IV). I only want to point out here that one of the striking characteristics of these tertiary geosynclines is the lack of abyssal sediments. They have therefore never been typical deepsea troughs. They never presented an aspect like that of the present deep-sea basins, e.g. the Banda sea.

<sup>1)</sup> G. L. SMIT SIBINGA. De geologische ligging der Boven-Triadische Olie- en Asphalt-afzettingen in de Molukken. Natuurk. Tijdschrift Nederl. Indië, Dl. LXXXVIII, 1928.

<sup>2)</sup> G. A. F. MOLENGRAAFF. On the geological position of the Oilfields of the Dutch East-Indies Proceed. Kon. Acad. v. Wet. Amsterdam. Vol. XXIII, 1920, p. 440-447.

<sup>&</sup>lt;sup>3)</sup> H. M. E. SCHÜRMANN. Über die neogene Geosynclinale von Süd-Sumatra. Geologische Rundschau. Bd. 14, 1923, p. 243, fig. 1.

If the Banda sea is considered as a geosynclinal basin, as is done by many of the authors mentioned above, it furnishes us with an example of a totally different type of geosyncline 1) viz. a type which, like the Caribbean sea has the characteristics of what Schuchert 2) calls a mesogeosyncline, and where sedimentation takes place down to great abyssal depth and corresponding facies. Escher's 3) views on the filling mechanism of such deep sea troughs is as follows. As the sedimentation in the central part takes place principally by sinking plankton the rate of accumulation is much slower there than in the bordering regions which are not only much shallower, but where important quantities of denudation products of the surrounding land areas are deposited. Escher points to the important part which must have been played by submarine slides in the filling mechanism of such a deepsea trough. If the aspect of the East Indian Archipelago does not considerably change, so that e.g. in the neighbourhood of the Banda sea extensive areas would be raised above the level of the sea and exposed to athmospheric erosion, the filling up of a basin like the Banda sea would require an endlessly long time. On the other hand the filling up of the tertiary geosynclines mentioned before, happened within a relatively short period of time, as has already been explained more exhaustively in Chapter VI, sub IV.

I have had an opportunity there to point out that still another type of geosyncline exists, which shows points of resemblance with Schuchert's polygeosyncline.

Evans <sup>1</sup>) has emitted the opinion that the expression geosyncline "has been employed too loosely to retain any scientific meaning". Indeed "we see that the term geosyncline has been altered from the original sense of  $H_{ALL}$  to the wider one of  $D_{ANA}$ , and that it is now applied to all marine basins of long-continued sinking and stratal accumulation. This condition of things has become so throughly engrafted in the literature of geology that it is probably impossible to change it" <sup>2</sup>).

Therefore it seems to me that Schuchert's conclusion is to be preferred viz. to "use the term geosyncline in the generic sense, as extended by Dana, and apply it to all the greater long continued down-flexured parts of the lithosphere".

<sup>1)</sup> J. H. F. UMBGROVE. Verschillende typen van tertiaire geosynclinalen in den Indischen Archipel. Leidsche Geol. Mededeelingen VI, p. 33-43, 1933.

<sup>2)</sup> C. Schuchert. Sites and Nature of the North American geosynclines. Bulletin of the Geological Society of America. Vol. 34, p. 151—230, 1923.

<sup>&</sup>lt;sup>3)</sup> B. G. ESCHER. Beschouwingen over het opvullingsmechanisme van diepzeeslenken. Verh. Geol. Mijnb. Genootschap voor Ned. en Kol. Geol. Ser., Deel III, p. 79–89, 1916.

<sup>4)</sup> J. W. EVANS. Regions of Compression. Quarterly Journal Geol. Society London Vol. 82, 1926, p. LXXV.

<sup>5)</sup> C. SCHUCHERT. The North American Geosynclines. Bull. Geol. Soc. America Vol. 34, 1923, p. 195.

# CHAPTER VIII.

# Relations between submarine topography and gravity field by PH. H. KUENEN.

In discussing the preliminary results of his gravity survey of the East Indies, Vening Meinesz has pointed out several important facts concerning the relations between the bathymetrical forms and the gravity field. He kindly proposed that I should treat this subject more in detail in this final report, because my own investigations as geologist of the Snellius Expedition had given me an opportunity for becoming familiar with the submarine topography of these parts. I gladly avail myself of his offer in the hope of being able to show how the gravimetrical data throw new light on the nature of the intricate morphological features and also how these forms may aid in the search for an explanation of the anomalies. In the following I will not describe the submarine shapes in detail. Those who are interested in this subject are referred to the forthcoming reports of the Snellius expedition 1), which also contain acknowledgements of sources of data, discussions on the accuracy of the soundings etc.

A few general remarks concerning the chart may prove of interest. It is founded on some 3000 wire soundings beyond the 200-m line and some 30.000 echo-soundings distributed along sections scattered over the whole area of the chart in deeper water, especially east of Java and Borneo. The length of these sections is about 60.000 km. The inaccuracy of the soundings is on the whole smaller than 50 m. For this investigation I could use the chart of the Snellius Expedition to the scale 1:1.000.000 and the sections drawn to the scale 1:100.000.

On a morphological basis the following subdivision of the East Indian seas had already been given by Molengraaff before the new data became available. To the northwest and to the southeast two great continental masses are found. The former comprises the southern part of the China sea, the Java sea, Malacca, Borneo, Java and Sumatra forming the southeastern corner of the Asiatic continent. In the southeast lies the Australian continent to which belong the Arafura sea and New Guinea. In the southwest we find the Indian ocean, in the northeast the Pacific. The narrow belt along Sumatra and Java and the eastern and northeastern parts of the archipelago are characterised by the island arcs and deep sea troughs with which we are principally concerned.

<sup>1)</sup> Scientific Results of: The Snellius Expedition, Volume V Geology, Part. 1. Geological interpretation of the bathymetrical results. Ph. H. Kuenen. The charts are contained in Vol. II, Part. 2, Chapter II.

When we take into account the results of the echo soundings we find that the deep sea basins fall naturally into two main types, each of which comprises two groups, so that we have four groupe in all. (See figure 51).

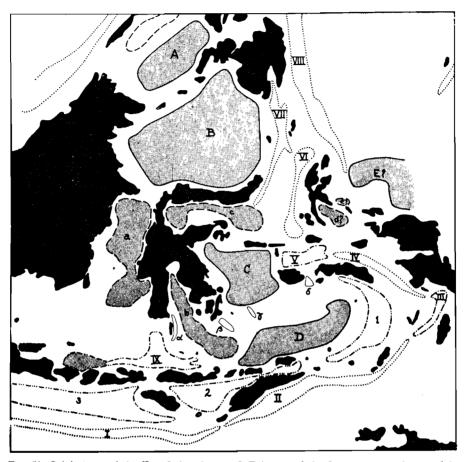


Fig. 51. Subdivision of the East Indian basins. A-E basins of the first group, a-e basins of the second group.

1-3 troughs of the third group, I-IX troughs of the fourth group.

The first type of basins has a flat and horizontal bottom with comparatively steep sides, so that the cross section is U-shaped. The anomaly of the gravity is positive. The basins belonging to this type can be subdivided into two groups.

The best example of the first group is the Celebes sea (B). The bottoms are flat and horizontal with a depth of about 5000 m. The groundplan is roundish or slightly elongated. The sides are relatively steep. From these characteristics it may be inferred that these basins were not formed in direct connection with horizontal compressive movements. Either they are remains of a formerly more extended ocean bottom, now cut off by the folding or faulting of intervening belts, or they were depressed by faulting or epirogenetic sinking.

Much is to be said for the latter explanation. Not only have Born 1) and Umbgrove 2) deduced from the geology of the islands, that these were formerly more extended, but the position of the basins, entirely surrounded by sial, also favours for these basins the idea of a secondary formation as depressed continental areas. The gravity field supports this view and the distribution of submarine faults, discussed in the Snellius Report, is also in its favour.

It is perhaps not superfluous to point out, that the edges of the basins are not fault planes, as the declivity is only a few degrees. They are either weak flexures or stepped faults, possibly both combined. We only want to emphasize the abrupt manner in which the flat bottom rises up at the edges, pointing to a primary vertical force, working over a large area with constant strength.

Besides the Celebes sea, the northwestern Banda basin (C), the southeastern Banda basin (D) between the Siboga ridges and the inner Banda arc and the southeastern part of the Sulu sea (A) belong to this group. The latter example shows the characteristic forms least distinctly. Little is known of the deep basin north of the northwestern part, the "bird's head" of New Guinea. The only echo sounding section at the western end lends support to the view that it might belong in this class of flat bottomed and deep basins (E).

The best example of the second group of basins is the Makassar Strait (a). The bottom is again flat and horizontal, now with a depth of some 2000 m. The sides are moderately steep. In ground plan the shape is strongly elongated, straight or curved, ending abruptly at one end and of abruptly varying breadth. The latter two properties and the angular cross-section besides the constant depth, all render a direct connection with folding movements improbable and point to a faulted origin or at least a primary vertical force.

Besides the Makassar Strait, the Gulf of Boni (b) and the Gulf of Tomini (c) west of the 124th meridian belong to this group. Possibly the N.W. Sulu sea and Halmahera sea (d, e) should be included, but data are too scarce to form a definite opinion. The Makassar Strait and Celebes sea, the Gulf of Boni and southern Banda basin hang together more or less. This points to an intimate relation between the two groups of the first type.

The second type of basins is more elongated, the members also forming more or less continuous strings, while the breadth varies gradually. These basins have tapering ends and show considerable though gradual variations in depth. The cross-sections are generally synclinal (V-shaped). These basins all lie alongside the belt of strong negative anomalies. The third and fourth group of basins belong to this type.

The third group of basins is represented by the Weber deep (1) and Savoe sea (2). The bottom is flat and horizontal in cross-section with steep sides all round; the shape is curved and tapers towards the ends with considerable variations in breadth. The depth varies from 7500 to 3000 m. Although the Savoe sea might also be included in the former group, it evidently belongs to the Weber deep from its similar position between the two Banda arcs. It is difficult to decide what tectonic agencies formed these basins. On the one hand the cross-section resembles that of a faulted graben. On the other hand the position between the folded Banda arcs, the curved shape, varying depths and tapering ends point more in the direction of a folded origin. The string of basins between Java and Sumatra on the northeast side and the ridge south of Java and along the Mentawei islands on the southwest

<sup>)</sup> A. Born: Ueber Werden und Zerfall von Kontinentalschollen. Fortschr. d. Geol. u. Pal. Bd. X. Ht. 32, 1933, p. 373.

<sup>2)</sup> This report.

side (3) forms the morphological continuation of the Weber deep and Savoe sea. Otherwise the shape recalls the next group of the typical deep sea troughs. On the whole the third group is the least satisfactory showing transitions to both the second and fourth group.

The fourth group, as stated, comprises the typical deeps sea troughs. They are distinguished from the former groups by the strongly elongated and generally curved ground plan, the varying depths (10.000 to 1500 m), the breadth only changing gradually and slightly and above all by the curved cross section, resembling a shallow syncline. They lie in an almost uninterrupted string along the ridge west of Sumatra and south of Java, the outer Banda arc, Halmahera and the Philippines. A second string is found along the western side of the Moluccan passage. Between the Soela islands and Obi a ridge cuts across the trough. To the northeast of Ceram a ridge along the axis divides the trough in two. Finally the Aroe trough (III) forms a complication. This basin ends abruptly in the north against New Guinea and has a flat and horizontal bottom with steep sides. It therefore forms a transition to the second or first group of troughs.

The deep Boeroe trough (V) presents characteristics similar to those of the Aroe basin, ending abruptly against Soela Sanana with an irregular but fairly flat bottom.

When we inquire into the probable tectonic nature of the typical deep sea troughs we arrive at a different conclusion than we did in the former cases. Those were found to give strong indications of a faulted origin, except the doubtful third group. Here we are led to assume compressive folding as the chief agent in the generation, the vertical movement being caused by a secondary resultant force, as in a syncline. The following arguments may be given. The typical troughs have the cross section of a shallow syncline, they are intimately associated with arcuate mountain chains that are generally believed to have been folded by compression, they have slightly curved ground plans, the trough line shows very gradual undulations, they do not appear to end abruptly, ridges along the axis are sometimes found, the breadth varies only slightly and gradually.

There are yet a number of minor basins that will not be discussed separately here, as they are small and as the gravity field based on relatively few stations. does not give sufficient details.

The subdivision in groups, as proposed here, is not quite strict. We already noted several cases of transitions between two of the groups (Aroe basin, Boeroe basin). The third group has characteristics of the fourth and second group.

Then it is not easy to say where the Flores sea (IX) should be classed. The cross section resembles that of the typical deep sea troughs. Its position on the inside of the Banda arcs and the strong variation in breadth, extending in the centre to a sideways arm pointing north, the constant depth of 5000 m of the trough line in the deep part, are three respects in which the Flores deep differs from the normal troughs. It seems doubtful, therefore, whether it belongs in the same class from a morphological point of view. The western end, north of Bali and Lombok comes close to the forms presented by the second group.

Notwithstanding the existence of these transitions, the most typical examples of each group are so very dissimilar, that they cannot be all attributed to the same cause. This becomes still more evident when the gravimetrical field is considered. We will therefore return to this subject presently.

Most of the positive forms of the morphology emerge over part of their length in the

shape of islands. The latter are discussed by Umbgrove, so that we can treat the ridges shortly.

An irregular row of slight elevations is found on the outside of the Java trough and its continuation along Sumatra, the highest of which form Christmas island and Corona reef. On the inside we find the ridge bearing the Mentawei islands and running on south of Java and from thence to Savoe and so on to the outer Banda arc. It can be traced as far as Soela Sanana where it joins onto the Banggai-Misool ridge at right angles.

The inner Banda arc forms the direct continuation of the high mountains of Sumatra, Java and the lesser Soenda islands. Beyond Banda it hangs together with the Oeliassers and Ambelau, but is also continued, beyond a deep passage, in the great virgation of the Siboga- and Luymes ridges, to which the Toekang Besi islands may also be counted.

The Philippines are connected with Borneo by three ridges; the Palawan ridge, an indistinct ridge in the centre of the Sulu sea and a broad, more or less double ridge from Mindanao. In the south the latter island sends off two more ridges; the Sangir ridge runs to the north arm of Celebes, the Talaud ridge follows the centre of the Moluccan passage and joins on to the northeast arm of Celebes. A second arm of the latter ridge, the Snellius ridge, brings about a connection with Morotai and Halmahera.

The southern arm of Celebes sends off a double arc of islands to the southeast and is indistinctly connected with the Soenda shelf by a broad plateau bearing many atolls.

Several of these ridges are built up largely of volcanic rocks but alle appear to possess an independent nucleus formed by (relative?) uplift.

A very important characteristic of a number of these ridges is the interchanging relationship of the crests by which they are formed. Frequently an en-échelon structure is presented, the crests running obliquely to the general trend of the ridge. Between Timor and the Kei group and between the Soela islands and Misool, the ridges south of Boeroe and probably also the Talaud ridge, Inner Banda arc, Soemba and Savoe, form the best examples of this class of mutual relationship.

The en-échelon structure is strongly in favour of compressive folding as the main agent in bringing about this relief, as opposed to block faulting that does not produce this relationship. The gradually curved ground plan and fairly constant breadth point in the same direction. It is not meant to imply that faults did not play any part, but they can only be looked upon as secondary and superficial expressions of a deeper lying movement of a folding nature.

For most of Celebes and for the Soela islands the ground plan and submarine forms are more in favour of faulted margins, cutting off blocks that may or may not be composed of folded strata.

We will now examine the gravimetrical character of the various groups of morphological forms more in detail.

The great, flat bottomed basins are characterised by strong surplus of gravity. In all four representatives of this group the positive anomaly is of the order of +80-+100 milligals with variations from about +50-+150 <sup>1</sup>). The region between the Toekang Besi islands. Boeroe and Banda, where the bottom of the great Banda basin is shallower and is thrown into strong relief, shows a markedly less pronounced surplus of about 40 milligals. The

<sup>1)</sup> Regional isostatic anomalies see Plate IV.

tentative addition of the basin north of New Guinea to this class of depressions is supported by the discovery of positive anomalies of  $\pm$  120 milligals at the western end of the basin.

Our second group of basins with a flat bottom, but shallower and elongated, are also regions of surplus, but it is interesting to note that with the smaller depth a decrease of the anomaly to about 50 or 70 milligals goes hand in hand. Only locally higher values are observed, and the averages are lower. The Halmahera basins, that were tentatively classed in this group, also show about  $\pm$  60 milligals.

Not only are the typical and well defined morphological characteristics of these two groups of basins of the first type found to be born out by similar anomalies, but the deduction that they are regions of faulted subsidence fits in very satisfactorily with the positive sign of the anomaly, which points to a general tendency to sink. Had the basins been formed by compression in the manner of a syncline, we would rather expect a negative anomaly corresponding to a tendency to rise. Gravimetry and morphology are thus found to lead to the same conclusion; a conclusion also arrived at by Umbgrove from the geology of the islands.

The connection between sinking and anomaly is not quite direct, however, for although the depth is nearly constant, the anomaly shows considerable variations and no more do all fields of gravity surplus coïncide with deep basins.

The third group of basins, the Weber deep and Savoe sea did not allow of a definite conclusion from a morphological point of view as to their mode of formation. Neither do they show a characteristic anomaly throughout. Nevertheless their position is characteristic, for they are situated along the line of strong negative anomalies. The also doubtful Flores basin shows a positive anomaly.

Although the typical deep sea troughs do not at first sight appear to be constant in gravimetrical character, their position with relation to the main belt of negative anomalies is highly significant. Without exception they all lie close too, and parallel with, this main belt. Thus the great Mindanao trough as soon as it deviates from the main belt to the southeast, decreases in depth and tails off to the east of Halmahera. Furthermore the troughs at both sides of the Moluccan passage bend outwards at the southern end, forming the two sides of a triangle, exactly where the belt of negative anomalies broadens out by the offshoot in the direction of the northeast arm of Celebes.

We already noted that the Aroe basin differs both in shape and position from the remainder of the Timor-Ceram trough. It is therefore important to note, that it lies further away from the centre of the belt of negative anomalies than any other part of the trough. Its gravimetrical character is slightly negative in the south, but at the northern end it approaches close to a few stations with positive anomaly. Possibly, therefore, it may even be found to show a positive anomaly here. The Boeroe basin also lies at a point where the line of negative anomalies curves away from the line of troughs, while in shape and position it resembles the Aroe basin. The strong positive anomaly may be due to the belts of surplus that accompany the line of dificit on both sides.

This brings us back to the problem of the transitions between the various types of basins. Now if these transitions were entirely arbitrary, now one, then the other characteristic of the other groups being presented, we might seriously doubt whether the subdivision had any real value. This, however, is not found to be the case. Thus the Aroe basin, besides forming a deviation from the line of negative anomalies, also presents the steep, faulted sides of the first groups together with their flat bottom and abrupt ending in the north against the New Guinea

mass. In somewhat less decided manner the Boeroe basin shows the same combination of characteristics of the first groups.

The same relationship in an even more pronounced form is presented by the trough on the western side of the Moluccan passage, where it bends away abruptly to the west in the broad, flat bottomed basin of the gulf of Tomini. This certainly indicates that these characteristics are not merely chance properties, but together lead to the demarcation of an entirely different type of form. The Flores trough also, although strongly recalling the real deep sea troughs, shows at the same time a positive anomaly, a constant depth for nearly its entire length, a greater distance from the line of negative anomalies together with a different position with relation to the arcs and a curious broadening in the central part for the middle depths.

The surprising constancy and equality of the depths of all the 4 or 5 members of the first group with a strong positive anomaly and the smaller but also constant depths of all the 3 or 4 members of the second group with less strongly positive anomaly are likewise indications of the validity of our subdivision.

I believe we may safely conclude that the differences between the groups have a deeper significance.

Little can be added from morphological data of the ridges to the treatment of their highest points, the islands, by Umbgrove in his section on the relations between geology and gravimetry. There are a few respects, however, in which the submarine forms throw new light on this subject. We saw that for some of the ridges the manner of interchange of crests and the enechelon structure indicate compressive tangential forces. All ridges with this character are situated above, or close too, the belt of negative anomalies, or, as in the region between the Toekang Besi islands and Ceram, there is a notable decrease of the positive anomaly prevailing in the neighbourhood.

Another feature worthy of note is that the new chart shows that Halmahera and Morotai are continued to the north in the Snellius ridge, that is in the direction of the anomaly-line. It had formerly been suggested (Brouwer), that they were connected to the east with the Palaoislands, in which case they would branch off from the trend of the mobile belt.

Finally we should note that the axis of the belt of strong negative anomalies does not bend outwards in the neighbourhood of the Kei-islands. This fact does not correspond to the theory, that the outer arc here bends outwards into the indenture of the Australian block. If the outer arc had moved forwards into the bay of the continent as represented by the tectonic line on the structural map of Brouwer, we would expect the line of negative anomalies to show a similar if less pronounced behaviour.

What actually happens is that the belt broadens both to the convex and to the concave side, while its centre follows along the inner side of the arc in a smooth curve. This behaviour accords very well with the morphological forms. We note that the concave side of the arc is a smooth curve and that the "adaptation" to the continent is not a moulding against the continent by an outward bending but a broadening of the arc by the addition of extra ridges on the outside.

One feature still has to be emphasized because of its great importance, not only for our problem, but also for the entire subject of earth features and their origin. This is the surprisingly small influence of the Australian continent on the phenomena as a whole. During the Snellius expedition the bathymetrical investigation of the critical region south of Soemba was also taken in hand and sounding lines were run with a view to fixing the major features in these parts. Formerly geologists and geophysisists ascribed a major or even the predominant part in the

structural development of the East Indies to the (relative) movements of Australia. When, however, we regard the new chart, we see that the principal elements of the relief are only influenced as to their general level and their course on the map, but hardly at all as to size and complexity.

This is most evident in the southeast, for which region the influence was formerly most emphasized (see fig. 52). The inner arc, coming from Java tails off gradually opposite the



Fig. 52. Shape and position of the Banda arcs opposite the Australian continent.

Australian continent. The outer arc forms a fairly smooth line from the ridge south of Java onto Savoe and the outer Banda arc. The Java trough is seen to continue directly into the Timor trough with a slight outward bend. It is for this entire length from 1 to 2 thousand meters deeper than the regions to its south and thus decreases from over 7000 to 2000 m in depth, while the sea bottom further out slowly rises from 5000 to 200 m. It will also be observed on comparison of the new chart with its predesessors, that the trend of the troughs from Timor to the Keislands is much straighter and smoother than was formerly believed. This is especially evident

when we bear in mind, that the true margin of the continent is parallel to the 1000 m line opposite the Tenimbar islands; it does not show the indenture presented by the 200-m line. The latter feature is only the consequence of a slight depression of the edge of the shelf to 3 or 400 m (For details we must refer to the report of the Snellius expedition, Volume V, Part 1). This failure of the Australian block to influence either the character or the intensity of the morphological features is strikingly born out by its inappreciable influence on character and intensity of the gravity field, as Vening Meinesz has already pointed out. He therefore assumes that, contrary to all expectation and prediction, the anomalies (and morphology) are a marginal phenomenon of the Asiatic continent, more or less independent of whether oceanic bottom or continental block be present along its outer edge.

A reservation as to the lack of influence of Australia is, that the *position* of the mobile belt may have been influenced, although in this respect also we are treading on very uncertain ground. It is true that the features are parallel to the edge of that continent, but we could with equal right state, that the edge of the continent is parallel to the mobile belt. Until we know what causes the generation of the structure we cannot state which view has more validity.

Molengraaff, Wegener and especially Brouwer believe, that the shape of the Banda arcs, and particularly the outer arc, were largely influenced by the form of the edge of the Australian block already given. We might compare this view to the making of a plaster cast, in which we attempt to determine which part is the cast and which the mould. As the Australian block is the older it must be the mould and the arcs were influenced in their shape by "casting" against this older mass.

There is, however, an entirely different possibility, that has only been proposed on scant stratigraphical evidence up till now 1). It is conceivable, that the Australian continent formerly extended across the belt of the present Banda arcs or even formed one continuous mass with the Asiatic continent. If subsequent mountain building had formed the arcs and troughs out of the margin of this continent, the parallel position as such would need no further explanation. In searching to determine which element guided the ground plan it would be as if we were attempting to find out whether the course of a canal were given by the position of its banks or vica versa, whereas the trend would actually be given by the plans of mankind. The plans, it is true, would have been influenced by the elements of the landscape, but canal and banks would run parallel by the nature of things. In the same manner the arcs, troughs and continental border would be parallel because they were formed together and side by side. Pre-existing elements in the continental mass would of course have influenced the position and course of the ultimately developing mobile belt, in the same manner as was the case during the formation of the Alps This was most ably demonstrated by Argand in 1916.

The new discoveries are not unfavourable to this rival hypothesis. In the first place we saw that morphology, gravimetry and geology all fit in with the conception of a former extension of the Asiatic continent to comprise at the least the whole of the East Indies, except the mobile belt following the line of strong neg. anomalies. For if we raise the depressed areas of the first and second group of basins, Celebes with the adjoining area is formed into one large continental mass.

<sup>1)</sup> H. Höfer: Das polynesische alteozäne Festland. Sitzb. Kon. Akad. d. Wis. Wien, Bd. 117, Abt. 1, 1908, p. 513-518.

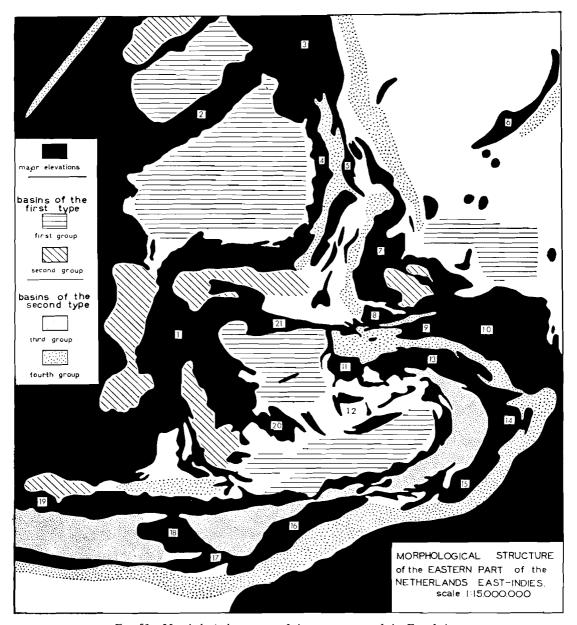


Fig. 53. Morphological structure of the eastern part of the East Indies. (To a certain extent it is a matter of taste how the precise shapes are drawn: compare fig. 51 and 52, showing slightly different forms).

1 = Celebes	8 = Obi	15 = Jamdena
2 = Sibutu-Basilan ridge	9 = Misool	16 = Timor
3 = Mindanao	10 = New Guinea	17 = Sawoe
4 = Sangir ridge	11 = Boeroe	18 = Soemba
5 = Talaud ridge	12 = Luymes- and Siboga ridges	19 = Bali
6 = Palao ridge	13 = Ceram	20 = Toekangbesi
7 = Halmahera	14 = Kei	21 = Soela islands

In the second place the remaining mobile belt consists morphologically of two arcs and an intervening and an exterior trough, also beyond the limits of the Australian continent, along Java and Sumatra. There is no avoiding the conception, already formulated by Molengraaff, but now enforced by the new data with double strength, that the troughs and arcs were formed together and by the same general process. The logical consequence of this conception is that the depressed and the raised areas were all originally of continental nature after the miocene folding. This conception is substantiated by Umbgrove in his chapter of this publication. For the period preceeding the miocene diastrophism the data are naturelly scarce. There is no geosyncline known that has doubtlessly originated from an oceanic bottom. Of the little that is known of the paleozoic and mesozoic geosyncline of Timor nothing indicates that it forms an exception, although its depth was temporarily great. This indicates the probability of a continental nature of the mobile belt for the entire stratigraphical column. The troughs along the outer side of the outer Banda arc are modern geosynclines for which we may reasonably assume that formerly, they also formed part of a (submerged?) continent. The geosyncline of Timor would then have migrated outwards in the normal way established for a great number of parallel cases (Grabau) 1).

In the third place we already noted that the convex side of the outer Banda arc runs parallel to the edge of the Australian continent opposite the Aroe basin, but that the concave side presents an even curve. Moreover the apparent outward bend at Jamdena is produced principally by an interchange of two crests. These characteristics cannot be explained by a gradual pressing together, a casting of the arc against the mould of the continent. We must assume that all elements, arcs, troughs and continental border, were approximately in their present relative positions to begin with. Gradually they were narrowed down and brought closer and closer together by compression, the relief possibly increasing through primary vertical forces.

These three points lead naturally to the conclusion that Asia and Australia are two masses touching along a mobile, but also continental, belt. A parallel to this case is found by passing westwards along the orogenetic belt to British India. The belt again passes between two masses, Asia and southern India. There is nothing exceptional, therefore, in the fact that in the East Indies the belt is bounded partly by a continent and partly by an ocean bottom on the southern side, for the same is seen to occur further to the west.

In my opinion the new data, therefore, point to the following relations. The Australian and Asiatic continents touch along a mobile belt, but they belong to one continuous mass in the same manner as Asia and southern Britisch India. The deep basins and troughs are depressed areas of the continent situated in the mobile belt and are not the remains of a former oceanic connection between the Indian and Pacific oceans. It would lead us too far to enter into the question of the continental drift of Australia. In the first Part of Volume V of the Snellius Reports this subject is considered and the conclusion arrived at there from quite independant data, is also that Australia always touched the East Indian archipelago in approximately its present relative position.

Before concluding it is well to point out, as Vening Meinesz already emphasized, that although we have found a striking connection between morphology and gravimetry, there is not an absolute coincidence. Thus the great Mindanao trough continues to the north beyond the

<sup>1)</sup> A. W. GRABAU. Migration of geosynclines. Bull. Geol. Soc. China III, 3-4, 1924, p. 207-349.

end of the belt of negative anomalies and the outer Banda arc deviates from the belt in western Ceram and Boeroe. With the smaller topographic features there appears to be even less coincidence.

The principal cause of these unexplained deviations is doubtless to be sought in the fact that the gravity anomalies are caused by effects in the deeper layers of the earth's crust, whereas the morphology is caused indirectly by the reactions of these to the surface layers. Even if a much more detailed knowledge of gravimetry and morphology were obtained, we could not expect to find rigid connections. Still it is to be hoped that closer nets of gravity stations and echo-sounding sections will in future be procured by which our understanding of many details will be made possible and which would also largely contribute to the elucidation of the whole complex of phenomena.

So much at least has become evident by tracing the relations between morphology and gravimetry, that the major features of both are caused by the same processes. The forces that depress the basins and elevate the ridges (relatively) are most intimately linked with those disturbing isostasy, whether these forces be consequent upon one another or identical.

# CHAPTER IX.

# Interpretation of the Gravity Anomalies in other areas.

# § 1. The Atlantic.

The interpretation of the gravity anomalies in the other areas cannot go as deep into the matter as it could be done for the East Indian Archipelago. In the first place the gravity material is less complete; in many cases it is restricted to only one crossing. In the second place the geological evidence is often scarce or entirely wanting and in the last place the morphology of the sea-bottom is in most of the cases imperfectly known. So for many of the areas not much more can be said than what was already mentioned in chapter IV. A few features, however, deserve our attention.

The main feature in the Atlantic is the positive average of the anomalies over a great part of this ocean. On page 101 we gave the figures, + 36 mgal for the Hayford-Bowie anomalies, + 32 mgal for the Heiskanen anomalies and + 28 mgal for the regional anomalies. The last  $\S$  of the first chapter gives a summary of the considerations with regard to such extensive fields of positive anomalies and we see that practically only two ways of explanation are available, a lateral compression of the Earth's crust or a descending current in the substratum. For the anomaly field in the Atlantic the first explanation is not satisfactory because it does not seem likely that in the border of the area this lateral compression disappears as quickly as it ought to do for explaining the sudden transition of the positive values over the deep sea to the normal or negative values on the European shelf. A second difficulty against this explanation is the high value of the compression that we should have to admit. For explaining an anomaly of + 30 mgal, we should have to assume a pressure of 15.000 kg/cm², if we suppose the pressure to act in one direction only and if we put the thickness of the crust at 30 km. For a thinner crust, as seems more probable in the ocean, we should have to assume a still higher pressure. So this explanation does not appear likely.

The second explanation on the other hand, which assumes a descending current in the substratum, can be readily accepted in the light of the hypothesis of convection-currents. As it has been exposed in § 9 of chapter I, we may admit a lower radio-activity for the oceanic crust than for the continental crust and so we must suppose the temperature of the substratum below the oceans to be lower than at the same depth below the continents. If the constitution of the substratum is homogeneous, this temperature difference must cause rising currents below the continents and descending currents below the oceans and so this distribution is in good harmony with the occurring of fields of positive anomalies in the oceans. This corroboration is a notable support of the convection-hypothesis.

Considering this result in relation to Wegener's theory of continental drift, there seems

to be a discrepancy. According to this theory the substratum in the oceans is not covered by a rigid crust capable of transmitting stress and so a sinking current in the Atlantic ought to bring about a tendency of the adjoining continents towards each other instead of away from each other. So, for bringing both theories in mutual agreement, we should have to suppose that the direction of the currents has changed since the Atlantic Ocean came into being. We should thus have to expect that geodetic measurements would nowadays show a narrowing of the Atlantic instead of a broadening. This whole conception does not appear to fit in with the arguments of the defenders of this theory.

A second important result of the gravity investigations in the Atlantic is the irregularity of the gravity field which is at once evident when we examine the profiles of Plate I. This seems likewise to disagree with Wegener's theory. If the irregular topography of the seabottom in the Atlantic, which has been found as well by the soundings of these expeditions as by those of previous ships and which is in good harmony with the similar results of the "Meteor" expedition in the southern Atlantic, if this irregular topography were caused, as Wegener supposes, by sialic remains of the disrupture zone which are floating on the substratum, the gravity anomalies, after isostatic reduction, ought not to show great deviations. The gravity field, however, is irregular and this points in another direction than Wegener's supposition. It proves the presence of numerous mass-disturbances and so we are led to suspect tectonic action in this area. This surmise is corroborated by the presence of earthquake-epicentra. Both arguments point to a crust which is capable to transmit stress.

A further proof of the rigid character of the crust may perhaps be obtained in the future by comparing the anomalies found in profile 3, west of the Iberian Peninsula, with those found in this part of the continent. When the continental gravity field would continue in the ocean, it must be considered likely that the oceanic crust reacts in a similar way on eventual forces as the continental crust. At this moment this comparizon cannot yet be made because the continental gravity material is scarce along the coast and it has not been reduced isostatically. The way in which the deviations of the anomaly-curves occur in this profile 3 makes it appear possible that such a continuation exists. The two most pronounced irregularities, in the stations 475 and 481, suggest a relation to the submarine ridges in these stations and these ridges give us the impression of being continuations of features in the Peninsula.

Admitting that the substratum below the Atlantic Ocean is covered by a rigid crust, the descending convection-current, which we have been led to assume under the ocean, must bring about lateral compression in this crust. The convection-current must be fed by converging horizontal currents below the crust, which must exert a viscous drag on the crust and so we have to expect lateral compression in the crust. So part of the positive anomaly must no doubt be caused by this compression and only part of it may be attributed to the descending current.

The presence of lateral compression in the crust below the Atlantic seems to be in good harmony with the earthquakes that are occurring here. The greatest part of the epicentra are situated over the Mid-Atlantic ridge and so the correlation of these considerations seems to tend towards the hypothesis that this ridge is caused by tectonic action brought about by lateral compression of the Earth's crust. This would corroborate the idea, already expressed by more than one investigator, that this ridge should be a young folded range in statu nascendi. It is worth while to examine what the gravity results have to say to it.

As we have already remarked in chapter IV, the two profiles 4 and 5 of Plate I, to the north and to the south of the Azores, show two similar features over the Mid-Atlantic

ridge. In the prolongation of the western group of the Azores, the islands Flores and Corvo, both profiles show a decided drop of the anomalies; profile 5 shows also a ridge on this spot which was discovered by the soundings of Hr. Ms. K XIII. In the prolongation of the central part of the Azorean Archipelago, the islands Graciosa, Terceira, Fayal, São Jorge and Pico, both profiles show another decrease of the anomalies although smaller than the above; the northern profile shows a ridge in this zone. Without further investigations it cannot be proved that these gravity features in profiles 4 and 5 are really evidences of continuous belts of lower anomalies over these zones but the general configuration seems to be in favour of it. It is also corroborated by the fact that in the crossing between the Canarian Islands and Porto Rico (profile 1) station 62 over the Mid-Atlantic ridge gives likewise a lower anomaly than the neighbouring stations.

So it is likely that in this part of the Mid-Atlantic ridge there are two narrow belts of lower anomalies over zones parallel to the axis of the ridge, and these belts, in connection with the presence of the earthquake-epicentra naturally suggest a similar phenomenon as that which has been found in the East Indies. When this comparizon has a real foundation, there is nevertheless a notable difference in size. The difference of the anomalies in the belt and beside the belt is only about one quarter of the value in most places of the East Indian belt. So if our supposition is true the root which has been formed in this case at the lower boundary of the crust, is considerably smaller. This may mean several things. Either it means a young formation and, accordingly, a small shortening of the crust, or a greater shortening but a thinner crust so that the amount of crustal mass which has escaped downwards is likewise small, or an old feature where the root has already partly disappeared by flowing away along the lower boundary of the crust. The earthquakes over the Mid-Atlantic ridge have not the same intensity as those in the East Indies but they nevertheless point to an activity in this zone during the present geological period and so the third possibility seems the least probable one. Further gravity research and more soundings in this interesting area will perhaps give more insight than can now be derived from the small number of gravity profiles.

We may finish our discussion of the gravity results over the Mid-Atlantic ridge by repeating what has been mentioned in chapter IV with regard to the island of São Miguel. The few available gravity data near this island seem to indicate that the island is a volcanic load superimposed on the crust. According to this, the island as it arises above this part of the ridge seems to have no local root at the lower boundary of the crust and so the gravity results appear to indicate that, as far as it is elevated above the ridge, it is purely volcanic. The data from which this conclusion is derived are, however, too few to consider it as final.

The same result has been obtained for the island of Madeira. The few available gravity data seem to indicate that the island, as far it arises above the surrounding sea-bottom, is a volcanic load on the crust without a local root at the lower boundary of the crust. Here again, however, more material will be needed before a final opinion can be given. The whole area round the island shows fairly strong positive anomalies. This cannot be caused by the fact, which is often thought to be responsible for positive anomalies on oceanic islands, that the volcanic material of the islands is heavier than normal rock because the positive anomalies extend far beyond the island. The excess seems to show some correlation to the depth of the sea (see profile 5) but the number of gravity values is too small to decide whether this correlation is accidental or real.

The gravity field does not show clear evidence of any tectonic belt between Gibraltar and the Azores which could be considered as a continuation in the ocean of the Sierra Nevada branch of the Alpine geosyncline, as it has been supposed by several geologists to exist. If there is something, it is not strongly pronounced in the gravity field and a closer net of stations will be needed for disclosing eventual traces of such a feature.

A remarkable effect has been found over the European shelf at the end of the Channel. It is clearly shown by the two profiles Nos 2 and 3, in which we see a narrow belt of negative anomalies over the shelf. The gravity defect has been found in the stations over shallow water but in one of the profiles the nearest station over deep water gives also a negative value of the anomaly. So here again we don't find an immediate correlation to the topography, although it seems probable that the feature is somehow connected with the shelf. Looking at the geological evidence in the neighbouring part of the continent, it is logical to assume a relation to the young-Palaeozoic folding of the Armorican belt, which appears to continue from Brittany westwards. In the light of the theory developed in connection with the tectonic belt in the East Indies, we may thus reasonably suppose that this belt is caused by the remains of the root of the old folded range which must have existed here. If this interpretation is true, we may conclude that this root has not yet entirely disappeared, although it probably has become smaller because of melting and flowing away and because of the rising of the Earth's surface in later stages of the mountain-range. Considering the remote period of the folding, this conclusion is worth while drawing attention to; it shows that probably even old formations can leave their trace in the gravity field.

#### § 2. The West Indies.

In the West Indies only a few gravity data have been obtained by the expeditions of this report and it would not be feasible to draw conclusions from them when no more was known in this area. There have, however, been operating here two American expeditions, which have given abundant gravity material, the expeditions of the U.S. Submarine S - 21 in 1928 and of the U.S. Submarine S - 48 in 1932 and this material has been further supplemented by gravity observations of the U.S. Coast and Geodetic Survey on the adjoining islands. So a good insight can be obtained here. The writer does not wish to give a complete treatment here of all the gravity material of the West Indies, but he will restrict himself to the two gravity profiles A I and A II of Plate I over the main island-ridge. The first of these profiles, over the Mona Passage west of Porto Rico, consists mainly of observations made by the expedition of Hr. Ms. K XIII and represented on the world-map; it has been supplemented by a few values obtained by the expedition of the U.S.S. S — 21. The second profile, over the same tectonic axis but more to the west, i.e. over Windward Passage east of Cuba, has been compiled from the results of the expedition of the U.S.S. S — 48. It has been added for giving an idea of the continuation of the feature to the west.

The examination of the profiles shows at once the striking analogy to the results in the East Indies. We find a similar belt of strong negative anomalies coinciding in the same way with a belt of tectonic activity and accompanied likewise by a deep, the Nares Trough north of Porto Rico. Profile A I shows a symmetrical profile analogous to the symmetrical profiles over the central part of the belt in the East Indies (profiles 2 to 16 of Plate II). Only in two

respects there is a slight difference, the belt of negative anomalies is somewhat broader, as the comparizon of the profiles shows, and it is not entirely beside the Nares Trough like the belt south of Java is beside the Java Trough, but it extends also under part of the deep. The second profile shows the asymmetrical type that is found in the East Indies west of Sumatra; it is similar to the profiles 18 to 21 of Plate II. The belt of anomalies is somewhat broader in these profiles than in those of the first type and the maximum value of the negative anomalies is smaller.

The combination of the coincidences of both types of profiles and of the geological and seismological evidence leaves no doubt about the identity of the phenomena in the East Indies and the West Indies. So north of Porto Rico we are also led to suppose a downward buckling of the Earth's crust and, accordingly, the formation of a root at the lower boundary of the crust in the same way as we have supposed it for the East Indies. Near Cuba we have to assume the other kind of crustal deformation as we have surmised it west of Sumatra, a sliding along each other of the two crustal blocks with a small component towards each other and a corresponding pressing down of the northern block. The transition of the two kinds of deformation is bound in the same way as it is the case in the East Indies to a change of direction of the tectonic belt. For the direction of the relative displacement of the southern block with regard to the northern block we must assume E.N.E., that is to say a direction which is nearly parallel to the Bartlett Trough south of E. Cuba. This direction has only a slight component at right angles to the belt near Windward Passage, but it encloses a greater angle with the belt north of Porto Rico and so it agrees with the above conclusions. The further gravity profiles observed by the American expeditions are likewise in good harmony with this assumption. Those over the Bartlett Trough, for instance, are consistent with the view that this trough is brought about by a slight component of the relative displacement of the two crustal blocks away from each other; this is in harmony with the above assumption about the direction of the relative displacement. This view would consider the trough as a rift-valley. The topographical relief of the bottom of the trough agrees likewise with this view, it shows evidence of recent subsidence of the crust.

For a more complete study of the gravity results in the West Indies, the writer may refer to the report of the expedition of the U.S.S. S = 48, in which H. H. Hess gives a note-worthy treatment of the subject  $^{1}$ ).

# § 3. The Pacific.

Beginning our examination of the results in the Pacific with the profiles P I, P II, P III and P IV which have been observed at right angles to the continental shelf between Panama and San Francisco, we have already noticed in chapter IV that they show the same character, a decrease of the anomalies, algebraically speaking, when going from the deep sea towards the shelf. This transition of the anomalies does not everywhere coincide with the same part of the depth-profile and so we find again that there is no direct correlation to the topography although there can be no doubt about an indirect connection to the shelf. An investigation shows clearly that no explanation is possible by supposing a wrong assumption of the isostatic compensation;

<sup>1) &</sup>quot;The Navy-Princeton Gravity Expedition to the West Indies in 1932", U.S. Hydrogr. Off. Washington, 1933.

this is already convincingly proved by an examination of the profiles because the curves for the different methods of reduction all show the feature in the same way.

In chapter IV we have concluded from the consideration of the profiles II and IV that probably the decrease of the anomalies does not extend far landinwards but that it is limited to a narrow belt, and so we are led to suppose a similar phenomenon here as in the East Indies. A further indication in this direction is the seismic activity along this coast which proves that it is likewise a tectonic belt. So, when we are right in attributing this similarity to a common origin, we may assume that here also the crust is buckling inwards. As, however, the difference of the negative anomalies of the belt and the adjoining positive values over the ocean is two or three times smaller than in the East Indies, the root must be likewise smaller in about the same ratio. We may thus express the same considerations as for the belts supposed over the Mid-Atlantic ridge; the smaller dimensions of the root may either be caused by a lesser shortening of the crust than in the East Indies, or by a thinner crust and a similar shortening, or, lastly, by an older formation which has already partly disappeared by melting and flowing away along the lower boundary of the crust. The seismic activity of the belt in the present period makes the latter possibility the least likely of the three.

For a thorough study of the whole feature a further gravity research over this zone will be necessary, extending farther oceanwards and farther landwards. For the landward continuation of the gravity field we dispose at this moment of the values determined in the U.S. by the "Coast and Geodetic Survey" and in Mexico by the "Direction de Estudios Geograficos y Climatologicos". The first survey only adjoins the most northern part of the belt. All the values in California show slight negative anomalies and so we may conclude that this part of the belt is not accompanied on the land-side by a field of positive anomalies like the belt in the East Indies is. For this part of the belt we have also information about the continuation oceanwards; profile IV may be extended by means of the values obtained during the crossing from San Francisco towards Honolulu and represented in the profile over the Pacific of Plate I. We see that the positive values soon disappear; they are apparently confined to a fairly narrow belt outside the coast. The positive anomaly of this profile, moreover, has no great value; it is only + 27 mgal for the Hayford-Bowie anomalies, +8 mgal for the Heiskanen anomalies and +29 mgal for the regional anomalies.

For the profiles I, II and III near the coast of Mexico, the gravity values observed in this country don't give much information. Profile III is far from the area which has been investigated and profiles I and II are nearer but still the next stations on land are at a great distance from the stations of these profiles. The major part of the observed fields shows negative anomalies of which the greatest value is found at Iguala at some 250 km to the N.N.W. of profile I; the Hayford-Bowie isostatic anomaly at this station is — 58 mgal. So here again we find no evidence of an extensive field of positive anomalies on the land-side of the belt. On the ocean-side the profiles show positive anomalies of some amount, but we don't know whether this field continues farther away from the belt.

So at the present moment we are not yet in a position for going deep into an attempt for explaining the feature found along this coast. We can only conclude that the available evidence seems to point towards a folding and buckling phenomenon of the Earth's crust of the same kind as it has been assumed for the East Indies and as it has been surmised in the palaeological period for the belt which now forms the shelf at the end of the Channel, but no final opinion can be given.

The crossing from San Francisco towards the Sandwich Islands shows a remarkably regular gravity field till near to these islands. The anomalies are about zero for the first half and for the second half they show slight positive values. As far as it is known, the topography of the sea-bottom for this part of the Pacific is likewise regular, save only one isolated elevation near to station 102. These results show a remarkable contrast to the irregular features of the gravity and topography that have been found in the Atlantic. The question might be asked whether perhaps this is caused by a complete or nearly complete absence of a rigid crust over the substratum in this part of the Pacific. Although no doubt the gravity field as well as the topography of the sea-bottom are in harmony with such a supposition, the writer does not feel inclined to this view. It seems that the feature along the Californian and Mexican coasts would be more difficult to understand from this standpoint because the presence of lateral compression of the crust in that zone seems to be better compatible with a rigid crust covering the substratum than without such a crust, although it must be conceded that a viscous resistance offered by the substratum might also be responsible for it. We should, however, thus have to assume a relative movement of the continent with regard to the substratum that does not seem consistent with the theory of convection-currents; according to this theory we ought in general to expect a rising current below the continent and, in consequence of this, an outward flow below the crust instead of a flow towards the continent. The gravity results near the Sandwich Islands, moreover, are also pointing towards a rigid crust on top of the substratum. So the writer is rather inclined towards this viewpoint and to explain the above facts of the regularity of the gravity field and of the bottom-relief in another way, viz as a result of the absence of orogenic disturbances. This is also in agreement with the absence of seismic activity in this area. As erosion is out of the question and as volcanism apparently does not occur here, there seem to be no causes that could bring about irregularities.

Part of the crossing between the Sandwich Islands and the Marianas shows the same characteristics of regularity of the gravity field and of the bottom-relief, but part of it is not so regular. Still further westwards from the Marianas, towards the Philippines, we are clearly in a different area where the gravity as well as the topography and the seismic activity concur in proving this area to be subject to tectonic disturbances. This is in good harmony with the views of Born 1) and other geologists, who consider this part of the Pacific as not of purely oceanic character but rather as part of an unstable belt with more or less continental properties to the east of the Asiatic and Australian continents. The question may be asked when examining the gravity field and the irregularities of the ocean-bottom between Honolulu and the Marianas, whether perhaps the boundary of this unstable area has to be put more to the east. A more thorough investigation of relief and gravity of this area will be needed for giving an answer to this question.

As we have already remarked in chapter IV, the gravity field from station 105, halfway between San Francisco and Honolulu, till station 125, at two thirds of the distance between Honolulu and Guam, shows a tendency towards positive values of the anomalies. The average is + 14 mgal for the Hayford-Bowie anomalies, + 14 mgal for the Heiskanen anomalies + 16 mgal for the regional anomalies. This is decidedly less than the average found over the eastern

<sup>1)</sup> BORN. "Der geologische Aufbau der Erde", Handbuch der Geophysik, herausg. v. Prof. Dr. B. Gutenberg, Gebr. Borntraeger, Berlin 1932, Bd II, Lief. 2,

and middle parts of the Atlantic. We might even ask whether perhaps it could be caused by the application of a wrong method of isostatic reduction, because, according to what has been said on p 20 and 36 of chapter I, the changing over to another depth of compensation may be imagined to have a slight effect on the mean anomaly of an extensive area. In this case, however. this explanation does not seem satisfactory because the three methods of reduction give about the same mean value although the depths of compensation are widely diverging. So, admitting that we have really here an extensive field of positive anomalies and that it will not prove to be elusive when more values to the north and south of the crossing will be available, we are lead to one or both of the two assumptions mentioned in § 10 of the first chapter, a lateral compression in the crust or a descending convection-current in the substratum. The writer is inclined to prefer the last assumption, firstly because the fields in the Atlantic and in the deep basins in the East and West Indies likewise point towards the presence of convection-currents and secondly because the foundation of this hypothesis, which predicts descending currents in the oceans, seems to him to be a sound one. Of course this assumption likewise implies lateral compression of the crust because of the reason which has already been exposed several times, the converging horizontal currents which must be assumed in this case below the crust.

In chapter IV we have discussed the few gravity data obtained in crossing the row of the Sandwich Islands near the island of Oahu. As far as this scanty material allows a conclusion, we have seen that it points to the island being a volcanic load on an unbroken crust. There seems to be no root at the lower boundary of the crust or, if there is one, it cannot have great dimensions, for else the regional anomalies ought to show stronger deviations than they actually do. So we may conclude that the present material points to a crust which has undergone no shortening at all. This would determine the islands as huge volcanoes piled up on the ocean-floor and pressing down this floor by their weight. The Brookes Trough to the northeast of the islands of Oahu and Hawaii could be well explained in this way; its shape is in harmony with this hypothesis as it shows a smooth curve without great depths. The fact that earth-quakes are rare in this area is likewise in good agreement with our view; only one great earthquake is known here, i.e. that of 1908 having its epicentre near the island of Hawaii 1). It is hardly necessary to emphasize that this result is in harmony with the viewpoint that this whole part of the Pacific has a purely oceanic character and that it is not subject to tectonic activity.

The crossings of the ridge of the Marianas near the islands of Guam and Yap have given a different result. The profiles P VI and P VII clearly show similar gravity deviations as the profiles over the tectonic belt in the East Indies. This is in good agreement with the fact that this belt is seismically strongly active 1); a great number of epicentres of world-wide earthquakes have been located here. It is likewise in harmony with the views of Born and other geologists that this part of the Pacific has to be included in the unstable belt of more or less continental character, which adjoins the Asiatic continent on the east and southeast side. Examining profile P VI more in detail, we see that it shows a belt of negative anomalies over the Nero Trough. which shows a resemblance to the belt in the East Indies, although the

<sup>1)</sup> Maps published by Commander N. H. Heck, Chief Division Terrestrial Magnetism and Seismology of the U.S. Coast and Geodetic Survey, Washington.

E. TAMS, "Die Seismizität der Ozeane und Kontinente", Zeitschr. f. Geophysik, Jahrg. 4, Heft 7/8.

difference of the anomalies is not as strong as it is there. For the regional anomalies it is only about 100 mgal and so the root that has been formed has not the same dimensions. This may be attributed either to a thinner crust or to a lesser shortening of it. The anomaly-curve is clearly asymmetrical; it is more or less similar to the curves of the profiles 18 to 21 in the East Indies west of Sumatra. If we may interpret this peculiarity in the same way as we have done it in chapter V for the East Indies, it would point to a relative movement of the two crustal blocks that has only a slight component at right angles to the belt. This would indicate a movement of the southeastern block with regard to the northwestern block towards the W.S.W. Assuming that this tectonic belt continues along the ridge of the Marianas towards the Asia Islands, the first block would be the same as that east of Halmaheira and north of New Guinea, that has been mentioned in chapter V in connection with the second direction of compression in the East Indies. We there have derived a relative movement of this block with regard to the East Indies likewise towards the W.S.W. and so this is in remarkable agreement with the above result. This gives a somewhat firmer base to these speculative considerations. More observations over this tectonic belt, reaching from the island of Hondo towards the Asia Islands, will, however, be needed for providing us with a better foundation for our conclusions.

The anomalies of profile VI near to the island of Guam point to a second root at the lower boundary of the crust under this island. The regular values of the curve of the Heiskanen anomalies indicate, as far as the few available values allow an opinion, that this root approximately corresponds to the island or, in other words, that the island is in isostatic equilibrium over its root in the way the Heiskanen method assumes. So it would appear as if the island ridge were another zone of crustal shortening and that the isostatic equilibrium, if it has ever been disturbed here, has been readjusted. Is this perhaps an older zone of tectonic deformation? A more thorough research will be needed for giving an answer to this question.

The second profile over this tectonic belt has been observed near the island of Yap. It is represented by profile P VII. This profile shows again a belt of negative anomalies over a trough in the sea-floor, but the belt is narrow here as, moreover, the trough is too, and the difference of the anomalies is still less than it is in the profile over Guam. The profile has a symmetrical character, as far as the observations allow to decide, and so it would appear as if this part of the belt encloses a greater angle with the direction of the compression. This is in good agreement with our conclusion from the former profile; looking at the world-map we see that the trough near Yap has its axis in a direction differing much more from the W.S.W. than the trough near Guam. This profile shows no evidence of a second root under the island like the profile over Guam.

Resuming we see that the profiles over this tectonic belt show enough similarity to the profiles over the tectonic belt in the East Indies to consider them as confirmations of the hypothesis of Born and other geologists that this belt has the same character and that the area must be reckoned to the unstable zone of geosynclines that accompanies the Asiatic continent on this side. A further corroboration of this viewpoint is given by the field of fairly strong positive anomalies in the deep ocean basin between the Marianas and the Philippines. In connection with the morphological resemblance to the deep basins in the East Indies, they point to a similar feature and the same supposition as to its origin, i.e. by descending convection-currents, seems indicated.

One slight disparity between both areas may perhaps be noted down. In the two profiles over the Marianas, the trough coincides with the belt of negative anomalies instead of being

beside the belt as it is the case in the East Indies. Does this point towards the absence of a surface layer that folds upwards over the zone of downward buckling of the main crust? Is this a proof that the feature is younger than in the East Indies or is it connected with a different constitution of the upper layer of the crust? We are surely not yet in a position to attempt an answer to these questions.

# § 4. Other Areas.

We shall refrain from attempting eventual interpretations of the gravity results obtained in the Mediterranean and in the Indian Ocean; for these areas the writer may refer to the short discussion of the results in chapter IV. In the Mediterranean only a few stations have been observed and so no interpretation would be possible in this area with its complicated tectonic history. There is still less reason to try doing so as the Italian and French Navies have organized gravity expeditions here and so, in a short while, an extensive material will be available, which will allow a more comprehensive study of this area. The values contained in this report may contribute to these investigations. About the crossing of the Indian Ocean from Socotra towards the northwest point of Sumatra no interpretation seems attemptable without taking into consideration the great gravity material of the "Survey of India" on the continent. This would mean a study in itself, for which this report is not the adequate place 1). For any such investigation, moreover, a continuation of the gravity survey in this part of the Indian Ocean in order to get a better view about the eventual prolongation of the continental gravity field in the ocean, will be desirable.

A short discussion may follow here of the results in the Red Sea, where the four gravity stations all show rather strong positive anomalies with an average of more than + 50 mgal, and of the three results near the Nile Delta, which show a gravity defect with an average of about - 20 mgal. The positive anomalies in the Red Sea agree with the positive anomalies formerly found along the coasts of the Red Sea by numerous observations of the Austrian Navy. In connection with the usual idea that the Red Sea is a sunken rift-valley, these positive anomalies have often been interpreted as the result of the rising of heavy simatic material in this rift of the crust. The writer cannot share this view. When indeed the crust has opened up the way for the simatic material to rise, this can never rise higher than a level, corresponding to isostatic equilibrium. A higher rising would go against gravity. So this level must be the maximum position that can ultimately be attained and this phenomenon ought to bring about negative anomalies tending at the utmost towards zero. Positive anomalies can never be explained in this way.

Examining the combination of positive anomalies and of subsidence, the resemblance is forced upon us to the deep basins in the East and West Indies, though it must be conceded that there is a difference in so far as the Red Sea is not situated in an area of tectonic activity. This resemblance suggests a similar phenomenon and so we might express the supposition that they have likewise been brought about by a descending convection-current in the substratum below the Red Sea. Such a current would indeed bring about a subsidence of the area as well as a positive field of anomalies and the writer must confess that no other admissible explanation of these two facts together has occurred to him. For arriving at a well-founded opinion, the continuation of the gravity survey over the adjoining countries will be necessary.

About the negative values over the Nile Delta, not much can be concluded save that

<sup>1)</sup> In 1932 an important study about this area appeared by Major E. A. GLENNIE of the Survey of India: "Gravity Anomalies and the Structure of the Earth's crust."

they point against any appreciable time-lag in the readjustment of the isostatic equilibrium of the delta after the deposition of the fluviatile material. For an interpretation of this gravity defect the material is entirely insufficient, but it may be pointed out as a vague possibility of an explanation that this area is considered by some geologists 1) to be the continuation of the Syrian orogenic arc and so we might perhaps suppose that we have here the same effect that has been found in other orogenic belts.

#### § 5. General Conclusions.

A few general conclusions regarding the gravity results of this report may be drawn. The first refers to the problem whether the substratum under the oceans is covered by a rigid crust or not. We have seen that, in general, the gravity results are in favour of the presence of such a rigid crust. This is certainly true for the largest part of the investigated area of the Atlantic; the irregularity of the field of anomalies seems difficult to explain when the sea-floor would be formed by the substratum even if it were partly covered by drifting crustal remains. It is likewise true for the western part of the Pacific; the gravity results seem to confirm the view expressed by BORN and other geologists that this area belongs to a belt of geosynclines which borders on the Asiatic continent. The results in the Pacific between the Sandwhich Islands and the Marianas show irregularities which also point in the same direction. Only the anomalies between San Francisco and the Sandwich Islands, with the exception of a belt along the Californian coast, seem to be regular enough for being compatible with the idea of an uncovered substratum, but here the gravity results along the above coast and near the Sandwich Islands give indirect indications that seem to be unfavourable to it. It needs hardly be remarked that these conclusions loose their strength when irregular currents or irregular changes of density could be accepted in the substratum; in that case the gravity field might show irregularities, independently of the presence of a rigid crust. These suppositions, however, don't appear to be likely.

The next point of consideration concerns the first characteristic mentioned in the beginning of chapter IV. The gravity results at sea seem to show a difference between the distributions of the negative and of the positive anomalies; the first seem by preference to occur in belts and the second in fields. The discussions of chapter V and of this chapter provide us possibly with a base for an explanation of these peculiarities. According to the buckling-hypothesis, the Earth's crust under great lateral compression tends to buckle downwards and forms a root at the lower boundary of the crust which betrays itself by negative anomalies. It is clear that such a buckling phenomenon must have a more or less linear course over the Earth's surface and cannot be distributed in fields. So the negative anomalies brought about in this way must also occur in belts. We have further seen that during the development of this tectonic phenomenon to a folded mountain-range and during the later stage of the peneplanation of this range, there seems reason to expect that this belt of negative anomalies will diminish, but that it does not seem to disappear entirely. So the discovery of belts of negative anomalies is in good harmony with this hypothesis.

For the positive anomalies, the situation is a different one. No doubt the above phenomenon will often be accompanied by positive anomalies alongside of the belt of negative

<sup>1)</sup> E. KRENKEL. "Geologie Afrikas".

anomalies, because the whole zone will rise in consequence of the tendency towards isostatic equilibrium, but besides this effect and more important than it, fields of positive anomalies have been found. For these fields, an explanation was suggested by descending convection-currents in the substratum and we have pointed out in the first place that such currents are likely to occur and in the second place that they must be expected to rise below the continents and to sink below the oceans. This distribution is in harmony with the fact that the gravity determinations at sea, contrary to those on land, have disclosed a tendency towards positive anomalies and that these anomalies generally occur in fields.

Lastly we shall shortly discuss the second characteristic mentioned in chapter IV. In many cases the anomalies of this report show the peculiar feature of increasing from the continental shelf oceanwards, and the same thing is found near many islands and submarine ridges. The effect is clearest for steep slopes. Here again the investigations of the previous chapters give some hold on a possibility of an explanation. It appears as if there are at least two effects that can bring about this correlation of an increase of the anomalies at about the same place where the depth increases. In the first place the slope may have been caused by a subsidence brought about by a descending convection-current in the substratum; this current must at the same time give rise to positive anomalies and so the correlation of the two features is automatically brought about. In the second place we can imagine that the steep shelf has originated by a tectonic folding phenomenon; several instances are known where a continent has thus been added to by an orogenic process along its borders. In this case we may again expect positive anomalies beside the shelf and negative anomalies below it. In the case of the submarine ridge south of Java, for instance, we may suppose that the correlation has been brought about in the last way. So, according to these considerations, the feature would not everywhere have the same cause.

This brings our discussions of the interpretation of the gravity results of this report to a close. Many considerations may only be looked at as tentative and future research will have to show whether they can be maintained.

# § 6. Conclusions about the Figure of the Earth.

The present gravity material is not sufficient to apply the Theorem of Stokes for determining the Figure of the Earth. Large parts of the Earth's surface have not yet been investigated and so, for an application of this theorem, the time has not yet come. Nevertheless the gravity material of this report may contribute in some ways to the problem of the Figure of the Earth. It may in particular give some indications about the cross-section at right angles to the rotation-axis because it provides us with a continuous ring of gravity values round the Earth. As it is well-known, several geodesists think that this cross-section is better represented by an ellipse with its great axis somewhere near Greenwich than by a circle. From the continental gravity material Helmert, Berroth and Heiskanen have derived formulas for normal gravity with a longitude term from which they deduced this ellipse. Is is worth while to see how the gravity values of this report agree with this longitude term. This is not encouraging. Superficially looking, the positive fields in the Atlantic and in the Pacific appear to be in harmony with it because they occur roughly speaking in the right place, but a nearer examination does not confirm this impression. The positive field in the Atlantic begins suddenly at the continental shelf and

this points strongly to its being connected to the crustal features instead of being caused by a regular flattening of the Earth in this sense. In the second place the positive field in the Pacific is so weak that it would only correspond to a much smaller flattening.

A more serious discrepancy, however, is found in the gravity fields in the West and East Indies. According to the above longitude term of the formulas, these fields ought to give a negative anomaly and this is contrary to the results that have been obtained. The gravity anomalies in the East Indies show an average of about +20 mgal and the average in the West Indies is probably likewise positive; the investigations have not covered enough territory for making sure, but it seems unlikely that the effect of the positive fields stated over the Gulf of Mexico, the sea west of Cuba and the Caribbean will be neutralized by the other areas. These fields, moreover, give also the impression of being connected to crustal features.

So the gravity results at sea don't confirm the supposition of the longitude term in the formula for normal gravity; they point in another direction, viz. towards irregularly distributed fields that are related to the phenomena in the upper layers of the Earth. An important part is played by the extensive positive fields which we have supposed to be connected to convection-currents in the substratum; if this supposition of their origin is true, the distribution of these currents dominates the problem of the Figure of the Earth. Over the rising currents fields of negative anomalies must be found and over the descending currents fields of positive anomalies. According to the discussion of the Theorem of Stokes in the second chapter this must in general bring about outward deviations of the geoid over the descending currents in the oceans and inward deviations over the rising currents in the continents.

In this regard it will be interesting to know the gravity field over the Indian Ocean. If our view-point is right, we might expect a tendency towards positive anomalies, while the longitude-term would imply negative deviations. So this ocean could perhaps provide crucial data about this problem. The results of the crossing between Socotra and Sabang cannot be considered as such because of their being too close to the great tectonic disturbances of the Southern Asiatic geosyncline, but a crossing more to the south might yield important results. To obtain such a crossing is one of the objects of the gravity expedition, planned in the next year by the Netherlands Geodetic Commission, from Holland to the East Indies via the Cape of Good Hope.

The viewpoint that the gravity anomalies don't show evidence of a regular flattening but rather of an irregular distribution over the Earth's surface, does not, of course, exclude that, when the results are developed in spherical harmonics, a second order term may be found which may be expressed in the shape of a longitude term. If, however, the above supposition of the cause of the anomalies is true, this term has no more physical meaning than terms of higher order. It is another question whether a formula with a longitude term may give a somewhat better approximation to the actual gravity field 1). This will no doubt be the case

<sup>1)</sup> During the putting into print of this report, a study appeared: The Continental Undulations of the Geoid by R. A. Hirvonen, Helsinki 1934, which contains an exhaustive treatise of this matter. The results can no more be taken into account in this publication and only a short remark can here be added that cannot do justice to this valuable work. It appears to the writer as if the results of Mr. Hirvonen, which are in favour of a longitude-term, are rather founded on a different interpretation of the existing deviations than on a deep-going difference of opinion about the deviations themselves,

because we may dispose of more constants for adapting the formula to the field. So, for predicting gravity, such a formula may be slightly preferable but then the introduction of higher order terms is also indicated. For interpreting the anomalies, the use of such a formula has to be discarded, because the anomalies that are thus obtained don't represent deviations from equilibrium. So, for that purpose, we have to revert to a formula without longitude term.

The same considerations that we have held for the gravity field, may be applied to the problem of the Figure of the Earth. The gravity results of this report don't point to a regular flattening of the cross-sections at right angles to the rotation-axis. They indicate irregular deviations from the rotation-ellipsoid and the deviations don't seem to agree to the flattening as it has been supposed by one of the above authors. A development of the deviations in spherical harmonics may perhaps give a second order term that can be represented by a flattening in this sense and so the triaxial ellipsoid may be a somewhat better approximation to the actual gooid than the rotation ellipsoid, but the flattening cannot be great and, as a reference surface, the slight improvement in approximation cannot be a set-off against the great complications which the introduction of such a triaxial ellipsoid would imply. Such an introduction would anyhow be premature because great parts of the Earth's surface have not yet been investigated and further research may fundamentally change the second order term. The adoption of a rotation ellipsoid has, moreover, the great advantage that it is a possible equilibrium figure of the Earth (save a slight deviation that may be neglected) and so deviations from this figure really represent deviations from equilibrium. This is not the case for deviations from triaxial ellipsoids. A last but all-important argument for adopting a rotation ellipsoid as reference surface is provided by the necessity that the reference surface must be in harmony with the formula for normal gravity and for this last formula we already argued to adopt a formula without longitude term.

The present gravity material does not yet allow an accurate determination of the geoid. Great parts of the Earth's surface are entirely devoid of measurements and so the Theorem of Stokes cannot yet be applied. The present material may, nevertheless, give some impression about the order of magnitude of the deviations. The material of this report has been used for this purpose. The regional isostatic anomalies of the ring of stations round the Earth have been supposed to extend to 20° north and 20° south of the equator and over the rest of the Earth the anomalies were assumed to be zero. To these assumed data the Theorem of Stokes has been applied and the deviations were computed. They gave a maximum outward deviation in the Atlantic of 100 meter and in the Pacific of 50 meter, while between those areas maximum downward deviations were found of — 40 and — 50 meters. So the deviations from the rotation ellipsoid are remarkably small. This expresses the good approximation provided by the assumption of isostasy. In terms of gravity this is shown by the smallness of the isostatic anomalies.