Geophysics. — *The Earth's crust deformation in the East Indies.* (Provisional Paper.) By F. A. VENING MEINESZ.

(Communicated at the meeting of February 24, 1940.)

§ 1. *Introduction.*

For the further investigation of the results of the gravity expeditions with submarines of the Netherlands Navy, the writer has prepared new tables for regional isostatic reduction; he has applied the system published in the Bulletin Géodésique N⁰. 29, 1931, to five different degrees of regionality. This system distributes the isostatic compensation of each topographic element over a wider area than the area of the element itself and the distribution in a horizontal sense follows the rule that the amount of compensation is proportional to the vertical displacement brought about by the bending of the Earth's crust under the weight of the topographic elements. For each element it adopts the bending-curve of the solution of HERTZ for the bending of an elastic plate floating on a fluid and submitted to a concentrated surface load. Introducing the length l given by

$$l = \sqrt[4]{\frac{m^2 E h^3}{12\,(m^2-1)\,(\theta_1-\theta_0)\,g}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where

E = modulus of elasticity of the Earth's crust,
m = coefficient of Poisson,
h = thickness of the Earth's crust,
$\theta_1 - \theta_0$ = difference of the specific densities of the plastic substratum and the topography,

the central part of the bending-curve of HERTZ was used up to a distance of 2.905 l from the concentrated load; the outward waves of small amplitude at greater distances from the center were neglected. The adopted curve is represented by fig. 1. So for each topographic element the isostatic compensation is assumed to be distributed in a horizontal sense up to a distance of $t = 2.905\,l$, having a maximum specific density in the center and this density falling to zero towards the border t according to the curve of fig. 1. The tables have been made for five different values of l, i.e. 10, 20, 40, 60 and 80 km corresponding to values of the outer boundary t of 29.05 km, 58.10 km, 116.20 km, 174.30 km and 232.40 km. They have been published in the Bulletin Géodésique N⁰. 63, 1940 and details about

these laborious computations may be found in "Verhandelingen der Kon. Akad. v. Wetenschappen, Afd. Natuurkunde", 1ste Sectie, Dl. XVII, N⁰. 3. The Netherlands Geodetic Commission has defrayed the expenses of the computations.

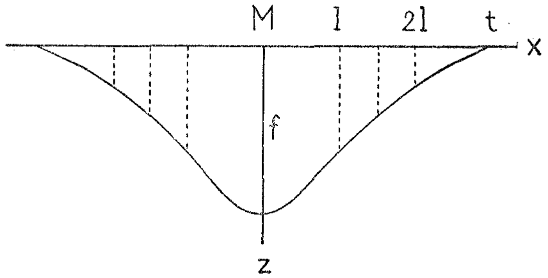


Fig. 1. Curve of the distribution of the regional isostatic compensation.

In these fundamental tables the compensation has been assumed to be distributed uniformly over a depth H below sea-level and the tables comprise all values of H from 0 to 60 km. From these tables other tables have been derived for practical use in which the compensation extends from a depth of 30 km down to a depth of $30 + 4.45\,s$, s being the height of the topography above sea-level. This last assumption corresponds to that of the Airy-Heiskanen tables for local isostatic reduction based on the principle of a crust of a normal thickness of 30 km and a density of 2.67 floating on a plastic substratum of a density of 3.27, each element being in hydrostatic equilibrium independent of its surrounding and sinking till a local root at the lower boundary of the crust is formed reaching from a depth of 30 km down to $30 + 4.45\,s$ km. The new tables, therefore, adopt the same system of hydrostatic equilibrium of the crust but they assume the root at the lower boundary of the crust to be broader according to a bending of the crust, instead of its sinking locally under the load of the topography. Incase we have a submarine topography, we have to introduce a value of s with a negative sign, the topography being now below sea-level, and we have to put $s = -0.615\,d$, if d is the depth, in order to take into account that the deficiency of mass has a specific density of 2.67—1.03; 1.03 has been assumed for the specific density of sea-water. The tables will be published in the course of this year.

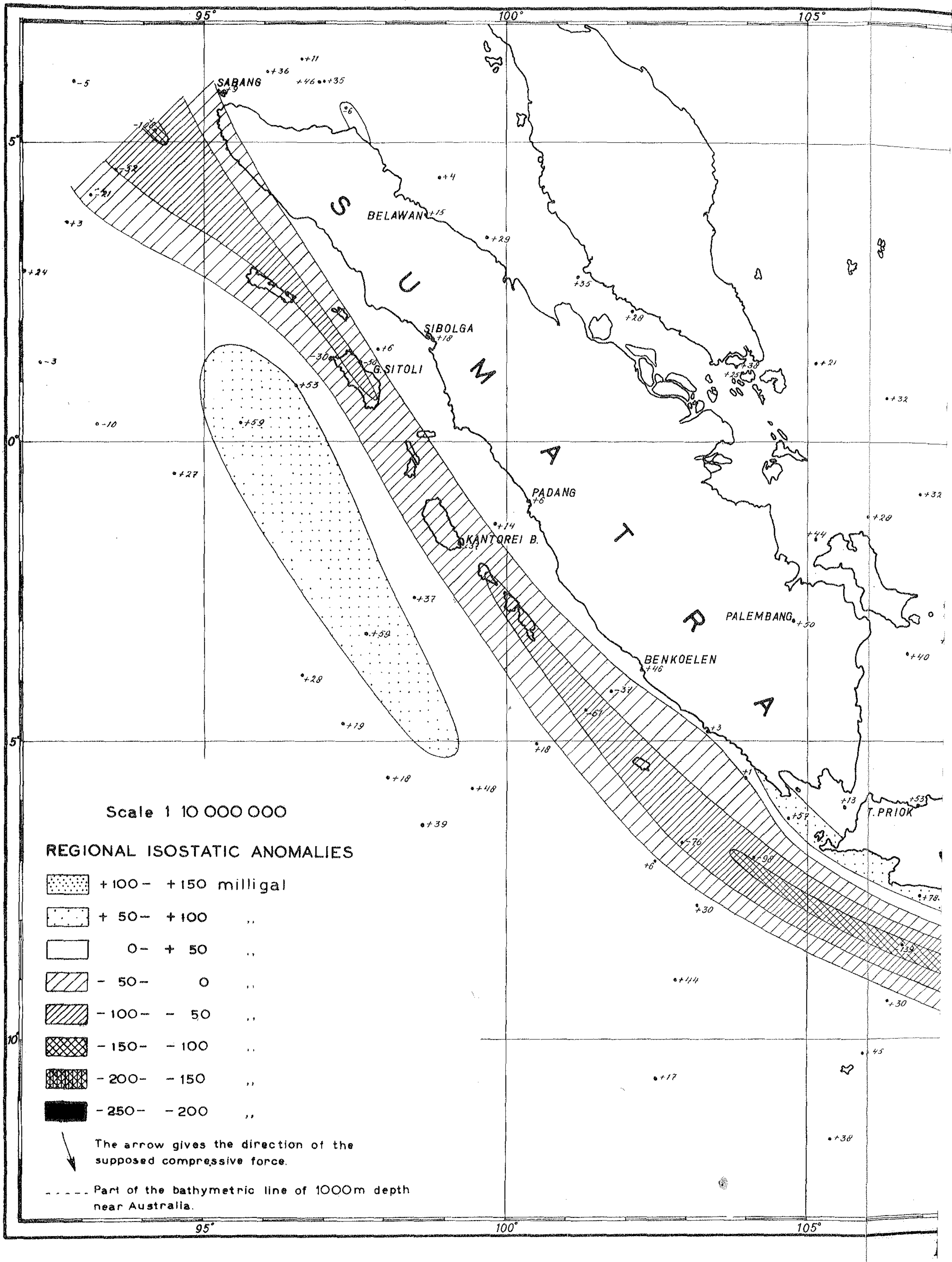
The Netherlands Geodetic Commission has used these tables for the isostatic reduction of all the gravity values obtained at sea. This paper contains a provisional publication of some conclusions derived from the results of these reductions for the East Indies. For each station six anomalies have been deduced, five according to the five degrees of regionality that have been mentioned and one for local compensation under the same conditions of vertical distribution. These last values as well as those for small regionality give an irregular picture of the distribution of the anomalies over the Archipelago; the anomalies for the three largest degrees of regionality show simpler features. So probably a large degree of regionality fits better the actual conditions in the Earth's outer layers. The most regular picture seems to be given by the anomalies computed with the tables for $l = 60$ km, which corresponds to an outer radius t of the compensation of 174.3 km. They are represented by the map of this paper which shows the isanomales for intervals of 50 milligals and as an example two gravity profiles are given in fig. 2*a* and *b*. The maps and profiles for $l = 40$ km and for $l = 80$ km also show acceptable distributions. A later publication by the Netherlands Geodetic Commission will contain the maps of the anomalies and a great many profiles for all the values of l and will thus allow a comparizon. The conclusions mentioned in this paper will be derived from the present map but nearly all of them would remain valid when the maps for $l = 40$ km or $l = 80$ km had been used.

§ 2. *The Map of the Regional Isostatic Anomalies ($l = 60$ km, $t = 174.3$ km).*

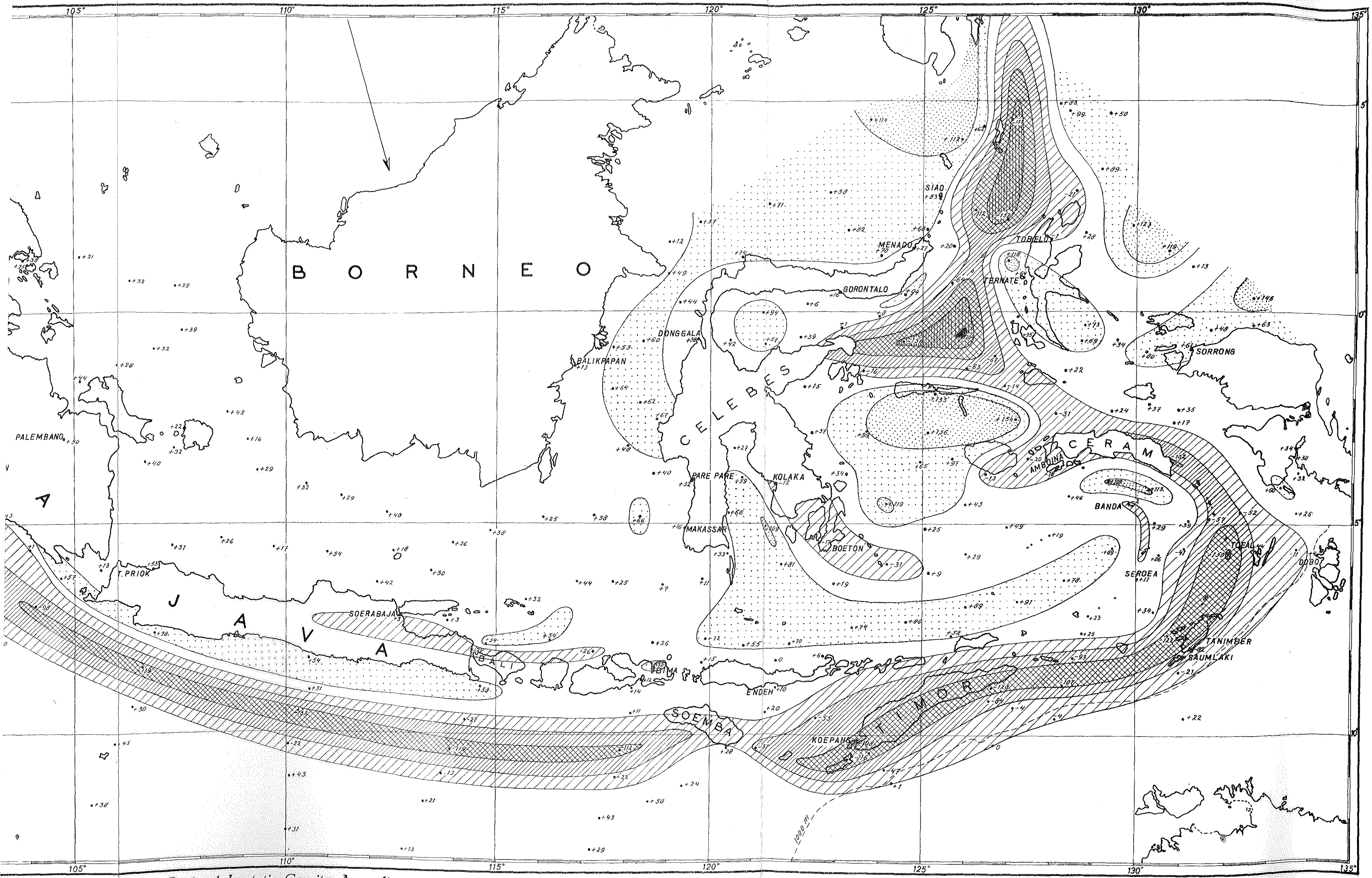
In considering this map the writer thinks that there are several reasons why an attempt is justified to explain the anomalies by taking as a base the simple mechanical picture of a rigid Earth's crust floating on a plastic substratum and subject to deforming forces; the present publication in fact is such an attempt. Of course he is perfectly aware that the real conditions in the Earth are more complicated. In the first place he will assume only one layer of constant density floating on a denser substratum of a specific density of 0.6 more than that of the crust. This is certainly not true as seismic and other evidence points to at least two and probably more rigid layers of increasing density downwards, but this simplification does not make a difference in principle for the main conclusions; they can be adapted without difficulty to the more complicated picture of more than one rigid layer. In the second place changes of state, e.g. from the crystalline to the amorphic, or differentiations and chemical reactions may occur. There is no doubt that these phenomena may affect the main occurrence; a further research may decide how far this will be the case. The object of this study is to see how far the above simplified picture will go in explaining the facts.

As a first reason justifying this attempt the writer may mention the fact that the regional isostatic reduction, based on this assumption, undoubtedly simplifies the anomaly map and so the way the topography is compensated is obviously in harmony with it. He must refer to the future publication of all the maps and profiles for proving this statement. For a second reason the writer may bring forward the success of the buckling hypothesis, which he advanced in 1930 for explaining the main feature of the anomaly map, the narrow belts of strong negative anomalies through the Archipelago. Although other attempts for an explanation have been made, it still remains the one that has found the widest support. It is based on the same mechanical picture and we shall now have to consider it a

F. A. VENING MEINESZ: THE EARTH'S CRUST DEFORMATION IN THE EAST INDIES.



Proc. Kon. Ned. Akad. v. Wetensch., Amsterdam, Vol. XLIII, 1940.



Regional Isostatic Gravity Anomalies in the East Indies ($l = 60$ km, $t = 174.30$ km) little more in detail as it is in fact one of the principal parts of our attempt at an explanation of the anomaly field.

As we shall point out in the next § an elastical plate floating on a fluid of greater density and submitted to a horizontal compressive force, will remain straight as long as this force is below a certain limit D_0 which we may call the buckling limit. When this limit is passed, waves will form and a slight increase of the force will then suffice for these waves to increase further in amplitude till one of them buckles. The writer assumes this to have occurred in the geosyncline in the East Indies under the effect of the tectonic forces. This corresponds to the great folding and overthrusting that has been found in the islands in the belt of anomalies. The buckling takes place in a downward sense and thus a great root of light crustal material is formed at the lower boundary of the Earth's crust. Because of its displacing the denser substratum this represents a large defect of mass and so the strong negative anomalies may thus be explained. We may adopt the supposition that a downward wave buckles downwards and not an upward wave upwards, because of the fact that the energy needed for the first is proportional to the difference of density of the substratum and the crust, which may be estimated at 0.6, while for the latter it must be proportional to the density of the crust of 2.7. This theoretical consideration is confirmed by the beautiful experiments of Dr. PH. H. KUENEN [1]), who compressed a plastic layer floating on water; gradually the layer forms waves and at a certain moment one of these waves buckles downwards. These experiments give a good support to our hypothesis. We may assume that in a further phase of the orogenetic development the upper layer of the crust will crumple upwards and gradually form a ridge that in its ultimate shape will compensate the defect of mass formed by the root. Thus the stage is reached of the complete mountain range with its compensation by a root of crustal material, about 4½ times as large as the range itself, which we find in the Alps and other folded mountain ranges. The main point of this hypothesis, therefore, is that the root is formed before the range itself and that this stage is now reached in the East Indies. The formation of a surface ridge is already going on in the East Indies; in most parts the belt of anomalies coincides with a submarine ridge or with islands as is shown e.g. by the profiles of fig. 2*a* and 2*b* but this ridge is still far too small to compensate the negative anomalies caused by the root. The formation of this surface ridge may also be brought about by the rising of the buckling zone because of the readjustment of the isostatic equilibrium or by other causes; we shall come back to this point. The buckling hypothesis may also explain another feature, i.e. the well-known fact that an orogenetic cycle begins by the formation of a geosyncline; this may be interpreted as the downward

---

[1]) PH. H. KUENEN, The negative isostatic anomalies in the East Indies. Leids. Geol. Meded. VIII, 2 (1936).

wave which afterwards, when the compression continues, buckles inwards.

These few words may suffice for giving an idea of the main points of the buckling hypothesis. The writer should now wish to look at the distribution of the phenomenon through the Archipelago. In the first place we may notice on the map that the anomalies point to a compressive force mainly working in one direction as indicated by the arrow, and not to stresses working in all directions. Where the anomaly belt cuts this direction under an angle of at least 45° the anomalies are large, but where the angle is small the anomalies are likewise small, as e.g. in the profiles west of Sumatra, in the profile from the Banda Sea towards New Guinea and also in the E.W. profile over Strait Surigao, north of Mindanao; this last profile outside the area of the map does not show negative anomalies at all. As the total of the negative anomalies in a profile over the belt is a measure for the size of the root that has formed at that place and, therefore, also for the amount of the shortening of the crust, this shortening must have been smaller for these last profiles than for the profiles elsewhere. This finds an explanation by the assumption of the compression working in the indicated direction because in that case the component of the compressive force in the sense of these profiles is small. The writer considers it a favourable point for the mechanical picture advocated in this paper that these differences in intensity of the negative anomalies along the belt may thus be explained by a simple supposition.

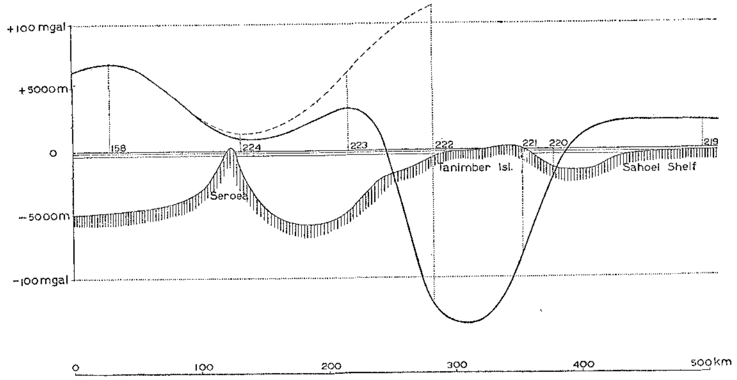


Fig. 2*a*. Gravity profile over Seroea and Tanimber Isl, Drawn line: regional isostatic anomalies ($l = 60$ km, $t = 174.30$ km), Dotted line: the same anomalies after subtracting the estimated effect of the root, Gravity Stations indicated by their number.

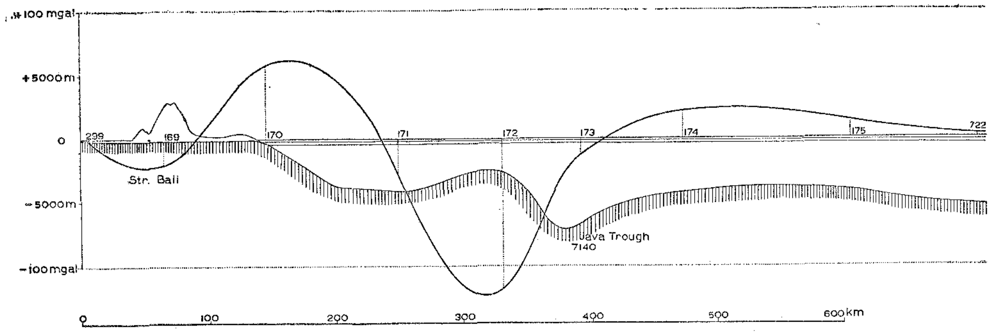


Fig. 2*b*. Gravity profile over Str. Bali southwards, Drawn line: regional isostatic anomalies ($l = 60$ km, $t = 174.30$ km), Gravity Stations indicated by their number.

The foregoing considerations about the anomaly-belt have already been expressed by the writer in previous papers; in what follows he wishes to add a new view-point partly based on the results of the new isostatic reductions. These results have led viz. to a slight alteration of the isanomales near the island of Soemba. The anomalies west of the island of Timor bring about a pointed course for the isanomale of —50 milligal near the S.E. Cape of Soemba and this has brought the writer to draw the isanomales in that neighbourhood as they are given on the map. This leads to a new vision on the irregularity of the belt of anomalies in this area. While the old anomaly map showed an interruption of the belt, the new one only points to a shift of the axis. This is better acceptable from the view-point of the buckling-hypothesis; an interruption would be difficult to understand because the question rises how the crust could be shortened to both sides of the interruption without the block of Soemba taking part in this shortening. A shift of the axis along a line which is about in the direction of the compression could, however, be better explained. In this connection it is worth while to notice that this shift occurs exactly where the Australian continent begins to face the belt; for showing this the map has been provided with the contour line of 1000 m depth. This coincidence suggests a causal relation and it is easy to think of a satisfactory explanation. Considering the great amount of sedimentation at the continental edge we could understand that a continent can be surrounded by a belt of weaker crustal material and in that case the buckling axis could not continue from its course south of Java straight towards the east but it should have to shift towards that zone of weakness; in its further course to the east it continues to follow the continental edge. We thus get a satisfactory explanation of the curious twist of the island ridge and of the anomaly belt in this neighbourhood. Here again the mechanical view-point provides us with a simple hypothesis. The fact that the island of Soemba does not show great folding or overthrusting is in good corroboration.

For further considerations about the buckling zone the writer wishes to refer to a future and larger publication, which will allow to go more into detail. Here other evidence regarding the mechanical picture advocated in this paper asks our attention. When we look at the anomaly map a periodicity in the occurrence of belts of negative and of positive anomalies strikes us. We notice it when drawing a line from the Celebes Sea towards the S.S.E.; we see here a regular succession of positive and negative anomalies, more or less in the shape of belts, and the distance of successive features is of the order of 150 to 200 km. In a N.S. profile through Java we find the same: a negative belt in the northern half of Java, coinciding with the oil-syncline, a positive belt over the southern half of the island extending over a strip of the Indian Ocean, the belt of large negative anomalies south of it and lastly a belt of smaller positive anomalies which does not show in the isanomales but which may be derived from the figures. West of Sumatra we find a similar periodicity. And in the West Indies which show a far-going analogy to the East Indies and where likewise a belt of strong negative anomalies has been found, a similar periodicity may be noticed. So it looks as if it is a regularly occurring feature and the question arises what this periodicity may mean.

Here again the writer thinks that the mechanical view-point may provide us with a better explanation than other lines of interpretation would be able to give; the obvious view-point is to interpret these alternating belts as brought about by a wave-formation in the rigid crust. The waves must give alternating deviations from the isostatic equilibrium of the crust, the upward wave causing positive anomalies and the downward one negative anomalies. We may find an important corroboration of this idea in the fact that the wave-length of 300—400 km is in keeping with that derived from the results of the new regional isostatic reduction; in the next § the writer will give a theoretical treatment of the phenomenon which will show the agreement. Another corroboration worth while mentioning is the fact that the profiles of the ocean bottom in many of the gravity profiles west of Sumatra and south of Java show a regular wavelike topography; the amplitude of the wave, i.e. the height of the topography, corresponds to the amplitude of the wave in the gravity anomalies when assuming no isostatic compensation and this is of course as it ought to be according to our supposition because the wave is entirely a deviation from the isostatic equilibrium. We do not find this same relation to the topography as clearly elsewhere in the Archipelago, but this may be explained by the complicated deformations of the surface layers and by the other surface effects of erosion, sedimentation and volcanological activity. The writer must again refer to the future publication which will contain all the gravity profiles for the corroboration of these statements; an instance may be seen in fig. *2b*, a gravity profile going S.S.W. from Strait Bali. He may also refer to that publication for a detailed comparizon of this interpretation with the old attempt made in 1934 in "Gravity Expeditions at Sea", Vol. II 1), where he attributed the positive anomalies in the deep basins, e.g. the Banda Sea and the Celebes Sea, to more or less local convection currents in the substratum and the belts of positive anomalies south of Java and west of Sumatra to an upwards drag of the crust because of the regional readjustment of the isostatic equilibrium of the crust over the belt of strong

---

1) Publ. Neth. Geod. comm., Delft 1934.

negative anomalies. Both explanations meet with difficulties when we go deeper into the matter and so the writer considers the present attempt not only as simpler but also as better.

The assumption of waves in the crust in the present period implies the assumption of a still working compressive force. This is in harmony with the fact that in a very recent period, in the pleistocene, folding has occurred in the oil-geosynclines of the Archipelago and also in E. Celebes and Boeton. It is also in keeping with the strong seismicity of the Archipelago. So we assume the crust to be subject to a compressive force in a horizontal sense, but we know that it is also subject to an upward force in the belt of strong negative anomalies because of the tendency to restore the isostatic equilibrium 1). We have, therefore, to take up the problem of the deformations of the crust by this combination of forces. We shall take this up in the next § and we shall have a look at the consequences of these results for the recent geology in the ensuing §.

§ 3. *Formulas for the deformation of a floating elastical plate under the effect of a vertical force and of horizontal compression.*

We assume the plate to have constant thickness and infinite dimensions. We further assume the problem to be two-dimensional and we shall here only treat of the simplest case of only one concentrated vertical force in upward direction. We put the origin of the coordinates in the point where the force acts and we take the horizontal axis as the X axis and the vertical one as the Y axis (fig. 3). We assume the deformations of the plate to be small enough that we may neglect the second and higher powers of dy/dx. In these assumptions we have neglected the curvature of the Earth, but it is easy to see that its only effect is an upward shift of the plate of $D/\theta_1 g R$, where D is the horizontal compressive force, θ_1 the specific density of the substratum and R the Earth's radius. Using the same letters and indications as introduced on the first page of this paper and introducing the quantities l_1 and D_0 given by

$$l_1 = \sqrt[4]{\frac{m^2 E h^3}{12(m^2-1)\theta_1 g}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$D_0 = 2\,\theta_1 g\, l_1^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

we find the following differential equation for the displacement y of the plate in vertical sense

$$l_1^4 \frac{d^4 y}{d x^4} + 2\,\frac{D}{D_0}\, l_1^2 \frac{d^2 y}{d x^2} + y = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

We see at once that for $D = D_0$ the solution shows a simple sine-curve and a further investigation by means of no longer neglecting the second

---

1) It is likewise subject to the vertical forces exerted on the crust by the topographic features but these forces are smaller and we shall neglect them here.

and higher powers of dy/dx shows that the amplitudes are quickly increasing when D increases slightly. So we see that D_0 is the buckling-limit of the Earth's crust, i.e. when D reaches this limit the deformations are growing so large that one of the waves will give way and a root will form. In the further investigations we shall suppose $D \leqslant D_0$ and for simplification we shall introduce the angle β given by

$$\frac{D}{D_0} = \cos 2\beta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

So β may vary from 45° for $D = 0$ to 0° for $D = D_0$.

The quantity l_1 has the dimensions of a length in the same way as the quantity l introduced on the first page by formula 1. When, however, the crustal wave is formed below the sea-surface we have not to introduce θ_1 in formula 2 but $\theta_1 - 1.03$, i.e. diminished by the specific density of sea-water. If we indicate the length we thus get by l_2, we have the following relation between the three values

$$l_1 = \sqrt[4]{\frac{\theta_1 - \theta_0}{\theta_1}}\, l \qquad l_2 = \sqrt[4]{\frac{\theta_1 - \theta_0}{\theta_1 - 1.03}}\, l \quad . \; . \; . \quad (6)$$

and introducing $\theta_1 - \theta_0 = 0.6$ and $\theta_1 = 3.27$ we find

$$l_1 = 0.656\, l \qquad l_2 = 0.719\, l \quad . \; . \; . \; . \; . \; . \quad (6A)$$

So the value of $l = 60$ km which has been adopted for the anomalies of the map, corresponds to $l_1 = 39.4$ km and $l_2 = 43.1$ km.

After introducing formula 5 in the equation 4, we find the general solution of 4 in the following shape

$$y = A e^{-ax} \cos(bx + \varphi) + A' e^{ax} \cos(bx + \varphi') \quad . \; . \; . \quad (7A)$$

in which A, A', φ and φ' are integration constants and

$$a = \frac{\sin\beta}{l_1} \qquad b = \frac{\cos\beta}{l_1} \quad . \; . \; . \; . \; . \; . \quad (7B)$$

When D does not reach the buckling-limit, i.e. when $a > 0$, this formula represents two waves of the same length of which one is increasing with x and the other diminishing. These waves are caused by other forces working on the crust besides the compression D and obviously the constants A and A' must be chosen in such a way that the waves are dying out to both sides of the outward force which causes them. If there is no outer force working on the crust, A as well as A' are zero and the crust does not undergo any deformation save of course the thickening by elastical compression; it remains plane. In our case of one vertical force working in the origin of the coordinates, we have the following set of formulas for y and its derivatives for positive values of x, representing a wave dying out for greater values of x, and for negative x we find the same curve towards the side of the negative x.

$$y = A e^{-ax} \cos(bx + \varphi) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (8A)$$

$$\frac{dy}{dx} = -\frac{A}{l_1} e^{-ax} \sin(bx + \varphi + \beta) \quad . \; . \; . \; . \; . \; . \quad (8B)$$

$$\frac{d^2y}{dx^2} = -\frac{A}{l_1^2} e^{-ax} \cos(bx + \varphi + 2\beta) \quad . \; . \; . \; . \; . \quad (8C)$$

$$\frac{d^3y}{dx^3} = \frac{A}{l_1^3} e^{-ax} \sin(bx + \varphi + 3\beta) \quad . \; . \; . \; . \; . \; . \quad (8D)$$

The length L of the waves is

$$L = \frac{2\pi}{b} = 2\pi\, l_1 \sec\beta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (9)$$

and as β varies from 45° for $D = 0$ to 0° for $D = D_0$ the wave-length varies from $2\pi\sqrt{2}\, l_1 = 8.90\, l_1$ to $2\pi l_1 = 6.28\, l_1$. Taking e.g. the case we shall treat of presently that $D = 0.6\, D_0$ and assuming a submarine wave of the crust and so, according to $l = 60$ km, $l_2 = 43.1$ km, we find $L = 303$ km. This is in good keeping with the wavelength of the anomaly-map as has been stated in the previous §.

For the determining of the integration-constant A we may use the value of the vertical force P_0 working on the crust in the origin. If H_0 is the total shearing-force in a cross-section perpendicular to the crust for x infinitely small but positive, we have, if the index $_0$ indicates values for $x = 0$

$$P_0 = 2H_0 + 2D\left(\frac{dy}{dx}\right)_0 = 2\theta_1 g\, l_1^4 \left(\frac{d^3y}{dx^3}\right)_0 + 4\theta_1 g\, l_1^2 \cos 2\beta \left(\frac{dy}{dx}\right)_0$$

which gives

$$P_0 = -2\theta_1 g\, l_1 A \sin(\varphi - \beta)$$

or

$$A = -\frac{P_0}{2\theta_1 g\, l_1 \sin(\varphi - \beta)} \quad . \; . \; . \; . \; . \; . \quad (10)$$

We may derive the second integration-constant φ from the value of dy/dx for $x = 0$. When the crust had not been broken in that point, we should have had to introduce $dy/dx = 0$. When, however, we identify this point with the buckling zone, other values are also possible, and so we have in general to introduce a certain given value for $(dy/dx)_0$. We may thus derive φ from

$$\left(\frac{dy}{dx}\right)_0 = \frac{P_0 \sin(\varphi + \beta)}{2\,\theta_1 g l_1^2 \sin(\varphi - \beta)} \quad \ldots\ldots \quad (11)$$

Introducing A and φ in $8A$ we find the curve for y.

In fig. 3 three cases are given, all for the same value of P_0, i.e.

fig. 3a $\quad \left(\frac{dy}{dx}\right)_0 = 0$

fig. 3b $\quad \left(\frac{dy}{dx}\right)_0 = \frac{P_0}{2\,\theta_1 g l_1^2}$

fig. 3c $\quad \left(\frac{dy}{dx}\right)_0 = \frac{P_0}{\theta_1 g l_1^2}$

and for each case three assumptions have been made for D. The drawn curve corresponds to no compression, i.e. $D = 0$, the point-dot curve to $D = 0.6\ D_0$ and the dotted curve to $D = 0.882\ D_0$. On purpose only positive values of $(dy/dx)_0$ have been chosen, because as a consequence of the downward buckling in a previous period, positive values seem more likely than negative values. They appear also to follow from some of the profiles, e.g. those south of Java of which fig. 2*b* is an instance. The vertical scale of the curves has been chosen in such a way that for the following acceptable values of P_0, θ_1 and l_1 the vertical scale is ten times exaggerated with regard to the horizontal scale, i.e. both scales are the same as those of the topography in fig. 2*a* and 2*b*. For P_0 a value has been adopted of 7.2×10^{12} gram per cm of the third dimension; this corresponds to a root of a cross-section of 1200 km^2 and a deficiency of specific density of 0.6 and this again is in keeping with the negative anomalies south of Java. For θ_1 and l_1 the values of 2.24 and 43.1 km have been adopted corresponding to a wave-formation below sea-level. Introducing this in formula 3 we find for the buckling-force D_0 8.3×10^{13} gram per cm of the third dimension, i.e. about $11\frac{1}{3}$ times as much as P_0. It is of course possible to introduce different values of $(dy/dx)_0$ to both sides and also to derive equations for more than one vertical force working on the crust, but the writer must refer to a future publication for these more complicated solutions.

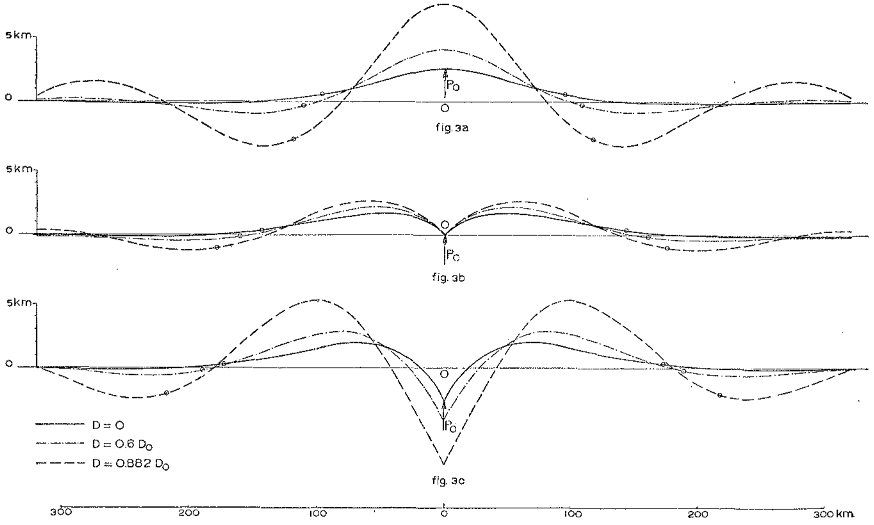


Fig. 3. Theoretical curves of crustal deformation under the effect of an upward force P_0 and a horizontal compressive force D.

We may derive interesting conclusions from fig. 3. In the first place we see that an increase of the compressive force D may bring about rising as well as sinking for the central zone, depending on the slope of the crust to both sides. Fig. 3*b* gives a case where this zone does not move at all. In all cases the waves to both sides increase in amplitude when D increases. When $D = 0$, i.e. when there is no lateral compression, these waves are insignificant and they become larger and larger when D increases. When D is near the buckling-limit they become nearly as large as the one in the central zone.

So we see that the effect of a change in the compression, even incase the force P_0 is kept constant, shows a great diversity, depending on circumstances, and this diversity is still more striking when we include cases where the slope of the crust to both sides of the central zone differs. This rather surprising diversity provides us with a means to adapt this solution to many different cases of behaviour of the crust and to bring them all back to one common origin. To point out these possibilities is one of the aims of the writer in this paper. In the next § he will make use of these possibilities for a few cases in the East Indies but an exhaustive treatment is out of the question here; the writer must defer this to a future occasion. He wishes to lay stress on the fact that the basic assumption opening these possibilities is a simple and acceptable one, the supposition of a compressive force working in the crust; the presence of the vertical force P_0 is no assumption but an observed fact directly derived from the gravity anomalies.

With a view to an hypothesis he wishes to make in the next § the writer has marked the points of maximum curvature in the downward waves of the curves of fig. 3. It is easy to derive their location from the equations 8 by equalling $8D$ to zero which gives

$$x = \frac{n\pi - \varphi - 3\beta}{b} \quad \ldots\ldots\ldots \quad (12)$$

For $D = 0$ these points of maximum curvature are farthest away from the deepest points of these downward waves; for increasing D they get nearer to these points and they coincide with them for the pure sine-curve which is obtained for D equal to the buckling limit.

§ 4. *Geological interpretation of the equations of § 3.*

According to the summary given by J. H. F. UMBGROVE in "Geological History of the East Indies" 1) the recent geological history of the islands of Timor, Tanimber, Kei and Ceram, all situated in the belt of strong negative anomalies, is the following. After the last period of strong folding and overthrusting in the upper miocene, a period of denudation of the elevated islands and subsidence followed so that in the pliocene the sea could invade them. Then trough faults and "graben" have been formed in the axis of the islands and about parallel to them, and finally towards the end of the pleistocene elevation occurred again and faulting. At the same time probably of this last elevation the troughs to both sides of these islands have sunk away.

In the light of the results of the previous § we may perhaps try to explain these occurrences by changes in the compressive force D. A decrease of this force may have brought about the subsidence in the first part of the pliocene and this is in keeping with the fact that in no part of the Archipelago folding occurred in that period. The writer does not think that the compressive force can have disappeared entirely because we may surmise that in that case the belt of negative anomalies would have succeeded in restoring its isostatic equilibrium. As since that time there has not occurred enough folding in this zone to give an easy explanation for these great anomalies, we must probably keep to the idea that they have at least for the greatest part originated during the great folding period in the upper miocene or earlier, and this probably implies that in no period since then the compression has disappeared entirely.

Towards the end of the pliocene or the beginning of the pleistocene folding begins to occur again in the Archipelago, e.g. in the oil-geosynclines, in Boeton and in E. Celebes and this appears to point to an increase of the compressive force. There seems reason to bring this in connection with the formation of the "graben" on Timor and the other islands and to attribute this likewise to an increase of the compressive force; such a reaction of the old buckling zone does not seem difficult to explain. The great vertical movements towards the end of the pleistocene indicate a further increase of the compression, which according to the results of the previous §, must gradually have brought about the waves that in the present period cause the alternating belts of positive and negative anomalies that have been found. The rising of the islands of Timor, Ceram etc. and the sinking away of the troughs to both sides could thus be attributed to this wave-formation; the deformation there would, therefore, have to belong to the type of fig. 3*a* or between fig. 3*a* and 3*b*

This explanation of the vertical movements makes it possible to understand that in other parts of the central zone slighter or even no rising has occurred. This may explain the great differences of elevation in this zone, the alternation of islands and lower parts between. South of Java we have a particularly low part of the zone and so we should have to classify this part under the types of fig. 3*b* or perhaps even 3*c*. We may find two remarkable confirmations of this view-point. In the first place the topographical profiles, as e.g. that of fig. 2*b*, show a downward slope towards the central part and so a value of $(dy/dx)_0$ leading to one of these types may be expected. As the horizontal and vertical scales of fig. 2*b* and fig. 3 are the same, we may directly compare the slopes in both figures. In the second place we find zones of positive anomalies at rather large distances of the central zone to both sides, of which that over the southern part of Java is one, and this is in better agreement with fig. 3*c* than with fig. 3*a*.

On the other hand the profile of fig. 2*a* over the Tanimber Islands comes near to the type of fig. 3*a* and this is in keeping with this part of the central zone having risen to a higher position than that south of Java. For making this clear the writer has subtracted from the regional anomalies of part of the profile, as given by the drawn curve in fig. 2*a*, the negative anomalies caused by the root of crustal material and the resulting anomalies are given by the dotted curve of fig. 2*a*. These anomalies may thus be assumed to be caused by the wave-formation of the crust and the curve in fact does fairly well agree with the type of the curves of fig. 3*a*. The writer considers this dotted curve as a first and still rather uncertain trial to free the anomaly-curve from the effect of the root. As we do not know its exact dimensions and shape this effect may be different and so the remaining part of the anomalies would also be different; this would mainly affect the part over the central zone. In consequence of this it might be possible that a nearer consideration would put the type of the dotted curve between that of fig. 3*a* and fig. 3*b*. It could not, however, quite be of the type of fig. 3*b* or still further away from fig. 3*a*.

In any case the inner Banda arc, represented in this profile by the island of Seroea, would coincide with a downward wave and thus it would correspond to the downward wave that in the profiles over Java and Sumatra, e.g. in the profile of fig. 2*b*, represents the oil-geosyncline. In view of the fact that both features occur in the same topographic axis, the axis of the greater and smaller Sunda Islands, this seems acceptable. The question arises whether we could thus understand the presence of strong volcanic activity in this axis. The writer is inclined to answer this question in the affirmative; a downward wave of the crust must bring about tension in the lower half of the crust or at least a diminishing of the pressure and this might explain the rising of magma. If this explanation is correct the location of the volcanoes ought more or less to coincide with the location

---

1) Bulletin of the American Association of Petroleum Geologists, Vol. 22, 1 Jan. 1938.

nearer to these points and they coincide with them for the pure sine-curve which is obtained for D equal to the buckling limit.

§ 4. *Geological interpretation of the equations of § 3.*

According to the summary given by J. H. F. UMBGROVE in "Geological History of the East Indies" 1) the recent geological history of the islands of Timor, Tanimber, Kei and Ceram, all situated in the belt of strong negative anomalies, is the following. After the last period of strong folding and overthrusting in the upper miocene, a period of denudation of the elevated islands and subsidence followed so that in the pliocene the sea could invade them. Then trough faults and "graben" have been formed in the axis of the islands and about parallel to them, and finally towards the end of the pleistocene elevation occurred again and faulting. At the same time probably of this last elevation the troughs to both sides of these islands have sunk away.

In the light of the results of the previous § we may perhaps try to explain these occurrences by changes in the compressive force D. A decrease of this force may have brought about the subsidence in the first part of the pliocene and this is in keeping with the fact that in no part of the Archipelago folding occurred in that period. The writer does not think that the compressive force can have disappeared entirely because we may surmise that in that case the belt of negative anomalies would have succeeded in restoring its isostatic equilibrium. As since that time there has not occurred enough folding in this zone to give an easy explanation for these great anomalies, we must probably keep to the idea that they have at least for the greatest part originated during the great folding period in the upper miocene or earlier, and this probably implies that in no period since then the compression has disappeared entirely.

Towards the end of the pliocene or the beginning of the pleistocene folding begins to occur again in the Archipelago, e.g. in the oil-geosynclines, in Boeton and in E. Celebes and this appears to point to an increase of the compressive force. There seems reason to bring this in connection with the formation of the "graben" on Timor and the other islands and to attribute this likewise to an increase of the compressive force; such a reaction of the old buckling zone does not seem difficult to explain. The great vertical movements towards the end of the pleistocene indicate a further increase of the compression, which according to the results of the previous §, must gradually have brought about the waves that in the present period cause the alternating belts of positive and negative anomalies that have been found. The rising of the islands of Timor, Ceram etc. and the sinking away of the troughs to both sides could thus be attributed to this wave-formation; the deformation there would, therefore, have to belong to the type of fig. 3*a* or between fig. 3*a* and 3*b*

This explanation of the vertical movements makes it possible to understand that in other parts of the central zone slighter or even no rising has occurred. This may explain the great differences of elevation in this zone, the alternation of islands and lower parts between. South of Java we have a particularly low part of the zone and so we should have to classify this part under the types of fig. 3*b* or perhaps even 3*c*. We may find two remarkable confirmations of this view-point. In the first place the topographical profiles, as e.g. that of fig. 2*b*, show a downward slope towards the central part and so a value of $(dy/dx)_0$ leading to one of these types may be expected. As the horizontal and vertical scales of fig. 2*b* and fig. 3 are the same, we may directly compare the slopes in both figures. In the second place we find zones of positive anomalies at rather large distances of the central zone to both sides, of which that over the southern part of Java is one, and this is in better agreement with fig. 3*c* than with fig. 3*a*.

On the other hand the profile of fig. 2*a* over the Tanimber Islands comes near to the type of fig. 3*a* and this is in keeping with this part of the central zone having risen to a higher position than that south of Java. For making this clear the writer has subtracted from the regional anomalies of part of the profile, as given by the drawn curve in fig. 2*a*, the negative anomalies caused by the root of crustal material and the resulting anomalies are given by the dotted curve of fig. 2*a*. These anomalies may thus be assumed to be caused by the wave-formation of the crust and the curve in fact does fairly well agree with the type of the curves of fig. 3*a*. The writer considers this dotted curve as a first and still rather uncertain trial to free the anomaly-curve from the effect of the root. As we do not know its exact dimensions and shape this effect may be different and so the remaining part of the anomalies would also be different; this would mainly affect the part over the central zone. In consequence of this it might be possible that a nearer consideration would put the type of the dotted curve between that of fig. 3*a* and fig. 3*b*. It could not, however, quite be of the type of fig. 3*b* or still further away from fig. 3*a*.

In any case the inner Banda arc, represented in this profile by the island of Seroea, would coincide with a downward wave and thus it would correspond to the downward wave that in the profiles over Java and Sumatra, e.g. in the profile of fig. 2*b*, represents the oil-geosyncline. In view of the fact that both features occur in the same topographic axis, the axis of the greater and smaller Sunda Islands, this seems acceptable. The question arises whether we could thus understand the presence of strong volcanic activity in this axis. The writer is inclined to answer this question in the affirmative; a downward wave of the crust must bring about tension in the lower half of the crust or at least a diminishing of the pressure and this might explain the rising of magma. If this explanation is correct the location of the volcanoes ought more or less to coincide with the location

---

1) Bulletin of the American Association of Petroleum Geologists, Vol. 22, 1 Jan. 1938.

of the maximum curvature of the crustal wave and this has led the writer to indicate these spots in the curves of fig. 3. We see that they are not found in the axis of the downward wave but shifted towards the side of the central zone and more so for smaller values of the compressive force, i.e. for waves that die out quicker with the distance to the central zone. For the profiles over Java this seems to be more the case than for the profile over the Tanimber Islands and the location of the volcanoes to the south of the oil-geosyncline appears in good keeping with this surmise. Besides this view-point the writer still thinks that the supposition he has formerly [1]) made regarding the occurring of volcanoes in belts on the inside of curved parts of the orogenetic belt, has a bearing on the subject, especially to explain that no volcanoes occur on the outside of a curve. This problem of the distribution of the volcanic activity in the Archipelago is, however, a complicated one, requiring much expert knowledge, and so the writer does not think he can do justice to it, certainly not in the few lines he can devote to it here.

An important point has still shortly to be mentioned. In his paper on "The negative isostatic anomalies in the East Indies" Kuenen mentions a problem brought forward by Mac Gillavry as an objection to the buckling hypothesis, i.e. the question how it is possible that the mean elevation of the eastern half of the Archipelago is below sea-level and probably lower than it has been in former geological periods, although the sial crust has been compressed; it looks as if this ought on the contrary to have brought about a rising of the mean elevation. There is no doubt that if the profile of fig. 2*a* over the Tanimber Islands should have to be identified with the deformation of the crust as given by fig. 3*a*, we must assume that the undeformed position of the surface should have to lie at a depth of some 5000 m or more. And so it appears as if there has been a considerable sinking of this whole area in recent periods. It is a great problem to find a cause for such a phenomenon which the writer is not able to discuss here, but he may shortly mention the possibility that this sinking could be explained by assuming a great convection-current system in the substratum with its descending current under this part of the Archipelago and rising currents under Asia and Australia or under one of these continents. Because of the drag exerted on the crust by this current such a current could at the same time explain the compressive force in the Archipelago.

The writer should not want to conclude this paper about the mechanical conception for explaining the gravity field and several geological features in the Archipelago, without mentioning also a serious difficulty for adopting it. The question is that the forces and stresses which must be assumed to work in the crust are considerable and larger than is generally supposed to be possible. If we adopt a value for D of 0.6 D_0 and if we take for D_0 the value derived in the previous §, we find the value of D to be 5×10^{13} gram per cm of the third dimension. Supposing the crust to have a thickness of 40 km we thus obtain a mean value for the compressive stress of 12500 kg/cm^2 and we get still larger figures for those parts of the crust where the bending causes additional compression. The writer cannot go deep here in the question at what figures we have to estimate these additional bending stresses and so he has to reserve that for a future occasion, but he wishes shortly to mention that they would become enormous if we kept to our simplified conception of the crust being one elastical plate. There is no doubt we have to come to a view-point nearer to the actual conditions in the crust for the attack on this question. In two ways we can understand that the bending stresses would be less. In the first place we may assume the crust to be composed of several layers which can more or less slide over each other and in the second place we can presume that the deformation for these large stresses, at least for parts of the crust, has not been of the elastical type but of the plastical or the block-faulting type. For taking up these problems we have to write the equations 1 and 2 in a more general shape by substituting

$$f = \frac{m^2 E h^3}{12(m^2 - 1)}$$

in which f is in general the ratio of the moment of force M working in the crust to the value $\frac{d^2y}{dx^2}$ of the curvature. We thus get

$$M = f \frac{d^2y}{dx^2} \quad . \; . \; . \; . \; . \quad (13A) \qquad l = \sqrt[4]{\frac{f}{(\theta_1 - \theta_0) g}} \quad . \; . \quad (13B)$$

The equations 6 for the values of l_1 and l_2 remain the same and also all the other equations and formulas.

The writer cannot go further in these problems here and so he wishes to conclude his paper with the general remark that this attempt for giving a mechanical explanation seems successful for many questions which are otherwise difficult to explain or to bring under one common view-point, but that the stresses and strains implied are large. He thinks, however, that it will not be easy to escape such a conclusion.

The writer wishes to express his thankful acknowledgements to his colleagues Umbgrove, Kuenen, Escher and Rutten for their helpful discussions; many view-points mentioned here may in fact have originated in these discussions, especially in the long talks he had about these matters with the former two. He wants further to acknowledge the assistance of Mr. J. van Dijk of the geological Institute of Utrecht for the making of the map and drawings. Lastly he wishes to recall that the whole gravity material is due to the great cooperation of the Netherlands Navy and to the helpful assistance of the Captains Mante and Van der Kun, of the Officers and of the men of the submarines on board of which the observations have been made.

---

[1]) F. A. Vening Meinesz, Gravity Expeditions at Sea, Vol. II, pp. 112 and 125, Publication of the Neth. Geod. Comm. Delft, 1934.