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SHEAR PATTERNS OF THE EARTH'S CRUST

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Abstract--There is much evidence of the existence of a system of shear planes in the greatest part of the Earth's crust, and it seems likely that some planetary cause must have brought it about. Two possible causes are investigated here, (1) the decrease of the Earth's flattening because of the slowing down of its rotation by tidal friction and (2) a change of the axis of the flattening because of a movement of the Earth's rotation axis with regard to the crust. Only the latter phenomenon gives a good explanation of the existing system of shear planes. A good correlation is obtained with the Earth's topography, with the distribution of volcanoes, with the gravity fields in several areas, and with most of the evidence about shear planes brought out by the "lineament" tectonicians Hobbs, Sederholm, Daubrée, Sonder, and others.

The hypothesis is not in harmony with the continental drift theory of Wegener. At the end of the paper some tentative conclusions are drawn about the origin of the continents.

CHAPTER I

Introduction and Summary

In this paper we shall, in the first place, investigate the stresses in the Earth's crust which, because of the flattening, must be brought about by a shift of the polar axis with regard to the crust. In Chapter II we shall discuss what causes are most likely to lead to such a shift. We have two possibilities. In the first place we may suppose the crust to be a rigid shell around the Earth which may move with regard to the interior; in this way the polar axis will continually coincide with other points of the crust. We might suppose this movement to be brought about by subcrustal currents exerting a drag on the crust. In the second place the axis of rotation may shift with regard to the Earth as a whole. We might look for the cause of such a shift in the attraction by the Sun and the Moon. A theoretical treatment of this problem shows, however, that although through this cause the axis of rotation of the Earth is moving in space, its movement with regard to the Earth is insignificant [see "References" at end of paper, HELMERT, 1884]. So, as other outside forces are very unlikely, we may practically neglect this possibility for our purpose.

The writer has undertaken this investigation of the deformations of the crust caused by the shift of the polar axis because of the fact that the new method of echo-sounding, which allows a much more detailed sounding program than the old laborious methods, has revealed a more or less regular linear topographic pattern, mostly in two directions, over extensive parts of the ocean floors. This, for example, has been found in a great part of the North Atlantic, in the northwestern part of the Indian Ocean, in the North Pacific, in the Gulf of Aden, and elsewhere. Considering the great extension of most of these areas we cannot escape the suggestion of a planetary origin, and among the few possible suppositions of this kind a shift of the polar axis seems to be one of the most acceptable. As we shall show in Chapter III, we shall find that it fits the facts remarkably well. We shall also examine another supposition, namely, a variation of the flattening--a slowing down of the Earth's rotation, because of the tidal frictions, is not unlikely. We shall find, however, that the evidence does not agree so well with this supposition. In Chapter II, we shall also find theoretical grounds against it.

Our subject falls into three well-separated parts, dealt with in Chapters II to IV. In the first we shall deduce the crustal deformation and the stresses for the above two hypotheses, and we shall derive the pattern according to which we may expect the crust to give way. In the second we shall examine the topographical, geological, and geophysical evidence in order to see whether this points to any such phenomenon having occurred. As has already been mentioned, this evidence is in favor of a polar shift. In the third we shall study the way in which the deformation itself or the presence of the resulting fault planes in the crust may have led to the coming into being of topography correlated to the pattern of these planes. This study will involve a discussion of a few other crustal problems; this last part thus has a more or less speculative character.

To simplify our deduction of the deformations and the stresses of the crust in Chapter II, we shall assume the crust to be a complete rigid shell of the same thickness everywhere. We cannot make sure about this last assumption as we do not know the deeper crustal layers under the continents and the oceans and neither do we know the temperature at the base of the crust in either part. There is, however, no need to feel doubt about it because of the apparently contrary evidence given by gravity, namely, the great difference in thickness of the sial crust in the continents and the oceans as given by the Airy hypothesis on the isostatic balance. This balance depends on the depth of the discontinuities of density, while the thickness of the rigid crust is given by the depth of the limit of rigidity; there is no reason why this last depth should not be nearly constant over the Earth's surface. The large radius derived from gravity for the regional distribution of the isostatic compensation of volcanic islands is certainly in good keeping with the assumption that the rigid crust under the oceans is not thinner than under the continents. It has been found for the Hawaiian Archipelago, for Madeira, for the Bermudas, for St. Vincent (Cape Verde Islands), for Mauritius, and in a somewhat lesser degree for São Miguel and Fayal (Azores).

The problem we shall deal with in Chapter II thus reduces to the determination of the stresses originating in a shell of constant thickness when the shape of the shell changes. Considering the magnitude of the Earth's dimensions with regard to the thickness of the crust, it is clear that this shell cannot prevent the Earth from adopting the equilibrium shape belonging to the new conditions, that is, a changed position of the axis of rotation or a variation of the amount of the flattening. It is simple to derive in each of these cases how much the different parts of the shell have to move in the vertical sense to assume the new shape; the movements in the horizontal sense are not known beforehand.

For attacking the problem we shall begin by determining the equations between the stresses and the deformations of the crust for the general case of a change of shape, and, having obtained them, we shall apply them to our two cases, first to the case of a change in the amount of the flattening (as by its axial symmetry it is the simplest of the two) and then to the more complicated case of a shift of the polar axis.

By introducing in these formulas the figures for the elastical constants, we find that the stresses in case of a change of the flattening are probably not quite sufficient for explaining a crustal catastrophe, but for the case of a shift of the poles they may attain values of 2000 kg/cm^2 or more, and so it is not likely that the crust is able to stand them without giving way. The question then arises along which lines we may expect this to occur. According to the older hypothesis of Mohr this must take place in the planes of maximum shear; in each point there are two of these planes at right angles to each other. As, however, the two directions predominating in the topography of the North Atlantic and of the northwestern Indian Ocean clearly do not enclose right angles, there seems reason to apply the more modern theory of Bylaard and Van Iterson, according to which the angle between the two directions depends on the differences of the three principal stresses. Chapter II investigates this question, and we shall find it plausible that the shearing of the crust obeys Bylaard's formula. Applying it to our two cases of crustal deformation we shall derive the resulting net of shear over the Earth's surface for each of these cases. To do this we shall choose the data in such a way that in the North Atlantic the two directions are in harmony with the topography. For the case of polar shift this involves a movement of the pole from the neighborhood of Calcutta to its actual position before the shearing occurred; we thus obtain Net 1, as given in Chapter III. If the pole is assumed to have also shifted since the shearing, the range of the possible suppositions about the shift that has led to the shearing corresponding to Net 1 is wider. Assuming a shift of 10° at right angles to the original polar shift we obtain Net 2 (see Chapter III).

In case the flattening has changed we find a Net as shown in Figure 9 (see Chapter III). This can not be brought into good agreement with the directions of the topography in the North Atlantic unless it is assumed that since then the pole has moved from a point near Grant Land to the present position; in that case we obtain Net 3 (see Chapter III).

Chapter II also discusses the question of whether we may expect the fault planes of the shear net to be normal to the crust. For some parts of the Earth's surface this must be the case, but for other areas deviations are likely. The amount of the tilt is indicated in the three Nets.

At the end of the discussion concerning a shift of the poles an estimate is made of the forces required for such an event, and it appears that the forces causing tectonic orogeny, which are probably exerted by subcrustal currents, must have been amply sufficient. Even the slight forces resulting from the "Polfluchtkraft," which have lately been redetermined by H. Kuiper [1943], may have appreciably contributed to it, although they can not have brought it about completely.

Chapter III investigates and discusses the evidence at the Earth's surface which may shed light on the question whether a shift of the poles or a change of the flattening have indeed occurred. We have three sources of information available, namely, topography, geophysical evidence, and geology. These three sources are successively examined and compared with the three Nets. As the submarine topography is not subject to erosion, it may be expected to furnish a more reliable base for the investigation than the land topography and so the study of the topography is mainly restricted to the oceanic areas. To determine the correlation of the topography of the oceanic areas with the three Nets we have measured for each ocean, as far as it is sufficiently sounded, the lengths of the topographic features in harmony with the Nets inside deviations of 12° and compared their sums to the sum of the lengths agreeing in the same way to the directions of an arbitrary Net for which we have chosen the directions bisecting the angles of the Net 1. The results are given in Table 3. For all the oceans together, that is, for about one-half of the Earth's surface, the sum for Net 1 is 2.34 times that for an arbitrary net, while Nets 2 and 3 show less correlation. We shall see that this ratio strongly points to a real relation between the topography and Net 1--the chances that this is accidental are negligible. The correlation is clearly shown also by our map. As it concerns the topography of such a great part of the Earth's surface, the result carries much weight in favor of the hypothesis of a shift of the poles. As the other two Nets show less correlation, we shall henceforth disregard them.

The great number of topographic lines correlated with our Net provides a problem to be dealt with in Chapter III. The view is defended there that when the growing stresses during the polar shift brought about the first plastic deformation, a kind of hardening occurred--which in this case may perhaps, at least partially, have taken place by the sealing up of fault planes by magmatic intrusions--and thus a new fault plane must have been formed elsewhere. The manifold repetition of this process may have led in this way to the great number of fault planes indicated by the correlated topography. It seems possible that finally, in analogy to the breaking of a steel strip after many zones of flow have become inactive by hardening, shear of a greater amount has occurred in a limited number of these fault planes.

The map shows also a curious correlation with the trend of many continental coasts. We may notice this, for example, for the east coast of Asia, the north, west, south, and northeast coasts of Australia, the west coast of North America, the northwest, northeast, and east coasts of South America, and the northwest and east coasts of Africa. It further strikes us that at least part of the coasts that are not in harmony with the shearing net are situated in areas where the value of the shearing stress is small, and that we thus can understand their deviating from the directions of our Net. As this correlation is difficult to explain, a special investigation of it is made in Chapter III, and there, in the same way as mentioned above, a ratio of 1.56 is obtained. Although this is less than that obtained for the submarine topography in general, it seems likely that a real connection exists. The problems involved are discussed near the end of Chapter IV.

Examining the topographic lines in harmony with our Net, it is found that many of them appear to continue over great distances and from one topographic feature to another. This is found, for example, along the east coast of South America continuing along the northwest coast of Africa, along the east coast of Spain, and also the west coast of the Malay Peninsula and of Sumatra, which may be continued along the west coast of Australia. (Other instances are mentioned in Chapter III, where they are shown on the map of Figure 10.) They may be expected to represent zones in which considerable shearing occurred; in this case we can understand that they must continue over great distances. The differences of the topographic features in the same belt point to the fact that differences in level on both sides of the shearing plane must have been brought about by other phenomena taking place after the shearing.

The geophysical evidence is given by gravimetric surveys and by seismological results. The first mention is made in Chapter III of the East Indies, where the distribution of the anomalies of gravity shows a clear correlation with the directions of our Net. Besides, the gravity field suggests that the compression of the crust in this area mainly takes place in one direction--this also coincides with one of the directions in the Net. The topography of the Archipelago likewise shows a correlation. In the West Indies the correlation of the gravity field and of the topography to our Net is less, although several topographic features are in good harmony with it.

A remarkable instance of a gravity field showing a strong correlation to our Net is provided by the detailed anomaly map of the Netherlands obtained by recent surveys. Former maps of this area based on a less detailed gravity survey show this much less clearly; they do not reveal the sub-surface structures with sufficient distinctness. Another instance of a good correlation is given by the gravity field in the Western Mediterranean.

For the seismological evidence we shall mainly revert to Sieberg's well-known studies about the geographical distribution of centers of earthquakes, which he bases on the combination of the seismological data with what is known about the geological features. The great majority of the maps given by him in his "Erdbebengeographie" in Gutenberg's Handbuch der Geophysik [1932] are in good harmony with our Net and thus give a valuable support to our hypothesis.

In Chapter III a short summary is also given of Visser's study on the correlation with our Net of the Earth's magnetism. It gives a curious result which merits further investigation.

The writer, not being a geologist, does not attempt to investigate and discuss the geological evidence touching the question whether a world-wide net of fault planes corresponding to the hypothesis is present in the crust; he must leave this difficult subject to geologists. Brief mention is made, however, in Chapter III of the many data collected by geologists Daubrée, Hobbs, Sederholm, Sonder, and other "lineament" tectonicians, who have long suspected such a net to exist, mainly because of geological, geomorphological, and topographical indications on the continents. Nearly all of this material supports our hypothesis, and, as it was obtained and published quite independently and long ago, this support carries much weight; the writer had no knowledge of its existence when he elaborated his hypothesis. The data mainly concern Africa, where Krenkel's well-known map shows lines in remarkable harmony with our map, and Europe, where many authors have contributed in collecting evidence and where also the topography of the Variscian and Alpine orogeny shows much correlation; data for North and South America and for Asia are also present. (For further details refer to Chapter III.)

Admitting that the combination of facts and correlations from all the sources mentioned is not likely to be accidental, another explanation than that of a polar shift seems improbable, because another phenomenon could hardly have brought about the same shearing net and the relations defined by complicated mathematical formulas. If our hypothesis is adopted, the question arises at what date did it occur. It seems likely that it occurred in one of the early periods of the history of the Earth's crust, probably long before the Cambrian, as it is difficult to account for the continental coasts having adopted their present general trends in any more recent period. If the correlation of the coasts is regarded as accidental, which does not seem likely, the answer to our question becomes more vague. In view of the correlation to the lines of Variscian orogeny, however, the date may be at least pre-Carboniferous and probably earlier.

It must be realized that many of the shear planes must have been maintained throughout great parts, or perhaps the whole, of the crustal history; in all cases where forces have since worked on the crust, the chances must have been great of differential movements of the separate crustal blocks and, therefore, of new shearing along these planes. If the crust had been covered by more recent sediments, these layers must have had insufficient strength for resisting the movements, and so the shear planes must have penetrated these layers also. It may, therefore, be expected that a continuous rejuvenation of the Net has taken place at the Earth's surface. Doubtless this must have been one of the main causes of the volcanicity of the alkaline type.

A second question arises concerning the causes of the supposed shift of the poles; this point has been touched on in Chapter II. The early date at which we must expect the event to have happened makes it impossible to give any definite answer, but we may, of course, attempt a speculation about it. Basing it on the hypothesis that the orogeny during the tectonically active periods of the crust's history has been caused by subcrustal currents--probably convection currents brought about by the Earth's cooling--it seems plausible that these currents, by exerting forces on the crust that are not in equilibrium, have been the cause of the rotation of the crust and, therefore, of the shift of the poles, in one of the first of these periods. It further appears possible that the shearing of the crust resulting from this event has put an end to this possibility of rotation of the whole crust because of the great amount of energy absorbed by the relative movements of the separate crustal blocks on which, henceforth, the subcrustal currents exerted their forces. Shifts of the pole of great extent would thus be excluded, and this would explain the fact that the present position of the pole still more or less coincides with the meridian along which the pole wandered before the catastrophe occurred. If great movements had since taken place, this coincidence would have to be considered as purely accidental, and, although there is no objection to doing so, the other viewpoint seems more satisfactory.

Chapter III finishes with a few general conclusions which may be drawn from our hypothesis. We may affirm that since the movement of the poles has led to the shearing of the crust, no continental shift of any appreciable amount can have occurred, because such a movement would have disturbed the Net. Moreover, the shearing of the crust can only have taken place in the manner described if the crust formed a rigid whole, and this excludes the idea of any continental shift of large dimensions. We need not stress the importance of this conclusion for geophysics, especially for the hypothesis of Wegener, which it forces us to abandon.

We may further state that the remarkable correlation of the shearing net with the topography of the Earth's surface provides us with a striking confirmation of the validity of Bylaard's hypothesis for the shearing phenomena in the Earth's crust. Bylaard himself has already affirmed and discussed this validity in papers concerning the crustal processes in the East Indies [BYLAARD, 1936, 1935].

We may remark, finally, that our hypothesis is based on the simple mechanical picture of a rigid crust floating on a plastic substratum and forming a closed shell around the Earth. This picture has already proved its value in several cases, for example, for the explanation of isostasy as given by Airy, for the adaptation of this explanation to regional isostatic compensation [VENING MEINESZ, 1939, 1941 a], and for the hypothesis of crustal buckling made to explain the belts of strong negative gravitational anomalies in the East and West Indies [see Chapter IV]. Although this picture is obviously too simple, because other processes must have played a part in the history of the Earth's crust as, for example, metamorphism, chemical processes, and differentiation, it in the main, nevertheless, covers the behavior of the crust sufficiently to explain most of its major phenomena. The present investigation seems again to confirm this viewpoint.

In Chapter IV the question of how the shearing of the crust can have brought about the correlated topography is discussed. In the first place the shearing itself must have caused ridges or troughs because of the fact that in general the plastic deformation in these zones must have involved displacements which at the surface had a vertical component. We shall, however, see that the amount of the rising or sinking must have been small, and, as it occurred so long ago, it seems doubtful whether even in the submarine topography, where no erosion has worked, traces of these features can still be present.

The second cause, the volcanicity, to which the shearing has no doubt given rise, must have had a much more important effect. It is sure to have continued up to the present time; the rejuvenation of the shearing in the fault planes caused by other forces working on the crust, as already remarked, must have reopened numerous passages to the magma. We have several indications that much of the submarine relief in the oceans has indeed this origin. In the first place most of the islands are volcanic, in the second place the linear character of the majority of the ridges points this way, and in the third place the irregular length profile and the variable breadth of these ridges thus find their simplest explanation. On the other hand, these arguments give a confirmation to our supposition that this oceanic topography is connected with shear planes in the crust.

Further confirmation of our hypothesis is given by the fact that the volcanicity of the alkaline type at the Earth's surface is practically confined to the areas where the critical stress caused by the polar shift has been large, that is, more than three-quarters of its maximum value. As the map shows, a remarkable instance of this is given by Iceland, which is situated on a narrow ridge of high stresses. This question is further examined in Chapter IV, in which mention is made of the fact that the gravity results hitherto obtained in the oceans are in harmony with our picture.

Besides the volcanic origin there are other ways in which we may imagine the presence of fault planes in the crust to have led to the initiation of correlated topography; these are successively dealt with in Chapter IV. In the first place, unevennesses of the planes may cause matter to be squeezed out during the shearing movements along these planes. Secondly, tilted fault planes, combined with tension or compression in the crust, must bring about topography; TABER [1927] first drew attention to this. These topographic features may take the shape of escarpments, "Graben," or "Horsts." Thirdly, epeirogenetic causes giving different vertical movements to the crustal blocks on both sides of a fault plane must also cause an escarpment along the line of this plane. In the fourth place, erosion of the fluvial, as well as of the glacial, type must bring out the presence of a fault plane; SONDER [1938] has dealt with this subject at some length, and so we may refer to this publication for details.

From study of the effect of tectonic action, we may expect that the presence of fault planes must have affected strongly the results of tectonic forces working on the crust. Adopting the hypothesis that in the area of the principal folding and overthrusting, the crustal shortening brings about a downward buckling process of the crust, we shall find that a shear plane, which also involves a zone in which plastic deformation has taken place, must lessen the force needed for this buckling, and so this last process will follow, by preference, the course of the plane. But, besides, the subcrustal currents probably responsible for the tectonic forces working in the crust must give, in many cases, different movements to the separate crustal blocks, and so shearing will occur in the fault planes between the blocks. As this must give rise, in general, to topography over these planes because of the effects already enumerated, we may expect that the orogenic belt shows other topographic ridges correlated with our Net of fault planes besides that caused by the main crustal shortening. We thus can understand a great part, if not all, of the complicated pattern of the tectonic trends in these belts. Examples given by the Alpine and southern Asiatic areas and by the East Indies and the Philippines are cited in Chapter IV. In the first area we recognize the directions of the Apennines, the Dalmation mountain ranges, the greatest part of the Carpathians, and part of the Alps themselves as belonging to our Net; in the second area the mountain ranges of Baluchistan and Burma seem to be correlated; and in the last area the part played by the fault zones of the west coast of Sumatra and of the eastern border of the Philippines may explain the origination of the great orogenic arc. There can be no doubt that the conception of a subcrustal current acting on a system of crustal blocks separated by fault planes may give a simpler explanation of the intricate pattern of tectonic orogeny than the supposition that forces have worked on an unbroken crust; in the last case the assumptions about these forces cannot be otherwise than complicated. The understanding thus obtained of these difficult problems seems to constitute a valuable point in favor of our hypothesis.

In the last place we shall attack the hardest problem of all, the explanation of the correlation of the edges of continental shelves with our Net. This introduces the following difficulty: It is well known that the seismic evidence is in favor of the granite layer of the crust being thicker in the continents than in the oceans; in part of the Pacific, and perhaps in the Arctic, this layer appears even to be entirely absent. According to the gravity results obtained in coastal profiles, this transition in thickness, in general, is rather sudden, and it coincides, or nearly coincides, with the edge of the shelf. On the other hand, it is clear that the shearing of the crust can not have affected its constitution and so this can not in itself have brought about the difference of the thickness of the granite layer. So we are bound to assume that these differences, at least for the correlated shelf edges, came into being after the shearing had taken place. The problem is how this can have taken place. In examining this problem we shall see that practically the only possible solution is given by the supposition that the course of a great part, if not all of the continental edges, is of a more recent date than the granite blocks of the continents themselves and that thus their formation can be posterior to the shearing catastrophe and can be correlated to its net of lines. This is immediately clear for those shelf edges where the trend is determined by recent orogeny, as, for example, is the case for the west coast of North and South America and the east coast of Asia. Considering the probability mentioned above that tectonic deformations have a preference to follow fault zones, it is clear that our problem is solved for these coasts; we need not be surprised to find that their trend shows a correlation to our Net. The figure for this correlation is mentioned on page 38; it is about the same as that for all the coasts taken together. From this result we can suppose that the directions of at least the majority of the other coasts have been determined likewise by orogeny, but that this has occurred in pre-Cambrian periods of such early date that this origin can no longer be traced by geological means. It is clear that thus our problem would be solved. In treating this hypothesis in Chapter IV we shall add a discussion of its compatibility with two recent suppositions about the origin of the continents, namely, those of Umbgrove and the writer, We shall find that this does not present difficulties but that we can not derive our hypothesis directly from one of them.

Concluding, we may say that the correlation of the continental edges with the shearing net can be explained by assuming that these edges, at least partially, have been brought about by tectonic phenomena. A little new light is thus shed on the problem of the origin of the continents.

CHAPTER II

The Stresses and Deformations of the Crust Caused by a Shift of the Poles or by a Change in the Flattening

As already mentioned in Chapter I, we shall investigate here the stresses and deformations which, because of the flattening, will occur in the Earth's crust when the polar axis changes its position with regard to the crust. Besides this main problem we shall also study the effect on the crust of a change of the flattening.

Before taking up these subjects we shall briefly discuss the possibility of one of these phenomena taking place. A shift of the axis of rotation with regard to the Earth as a whole does not seem likely. It is obvious that it could only be brought about by external forces, and in this regard there are practically present only the attractions exerted by the Sun and the Moon. It is true that these forces, because of the flattening, or to be more exact because of the difference of the moments of inertia around the axis of rotation and around an axis in the equator, affect the rotation of the Earth, but the study of this effect [HELMERT, 1884] has shown that only the change of position of the axis of rotation in space is important; the disturbance of the axis with regard to the Earth is small and quite negligible for our subject.

The second possibility of a shift of the poles with regard to the crust, namely, by a gliding of the crust over the Earth's interior, seems more acceptable. There is no doubt that the deeper layers are plastic and that they allow movements under small differences of stress; otherwise the isostatic balance could not be maintained so well. There is no objection, therefore, in assuming the presence of subcrustal currents, possibly caused by some kind of convection brought about by the inward temperature gradient. Such assumed currents may explain tectonic forces in the crust, which otherwise are difficult to account for. This subject is further discussed in Chapter IV. The system of these currents must exert a drag on the crust, which, if we consider the crust as a rigid whole, will have a resultant momentum tending to rotate the crustal shell around the interior.

Besides this possible cause there is another to be mentioned, namely, the "Polfluchtkraft." The momentum resulting from these forces, however, is small, and, according to a recent investigation made by H. KUIPER [1943], it is questionable, although just possible, that it is in itself sufficient to cause large shifts of the poles; it may have contributed to the movement needed for our hypothesis. We shall find hereafter that this last movement must have taken place along the meridian of 90° east of Greenwich and that the middle of the start and the finish must be situated at latitude 55° north. As Kuiper found [see also MILANKOVITCH, 1938] that the maximum orbit which the "Polfluchtkraft" may possibly have brought about begins at 59°.2 north and 72°.7 east, we see that it does not deviate much from the second part of the orbit required for our hypothesis. As the "Polfluchtkraft," however, is caused by the present configuration of the continents and the oceans, it is possible that it contributed to the shift of the poles if this movement occurred later than the formation of the continents, and we have already mentioned in Chapter I that the correlation of the net of deformation to the continental coast lines rather points in the opposite sense. It still remains possible, however, that at the time of the polar shift other topographic features were present and that the corresponding Polfluchtkraft contributed to the shift; it may even have caused it entirely.

We shall now consider the possibility of a change of the flattening. There can be no doubt that such a change must have occurred; the tidal friction is sure to have slowed down the Earth's rotation, and this must have affected the flattening. Besides, possible changes of the Earth's diameter or shifts of its masses must likewise have had an effect, but it is clear that since the solidification of the Earth's crust this can not have been important.

JEFFREYS [1929, Chapter IV] deals at length with the subject of tidal friction. He derives the slowing down of the Earth's rotation from the secular acceleration of the Sun and the Moon, and the result given by him is that 1600 million years ago the period of rotation must have been 0.84 of the present day. This corresponds to a flattening of 1/210. Still longer ago the tidal friction must have been greater, because the Moon was nearer the Earth, and shortly after the formation of the Moon by the disruption of the Earth the day must have been about five hours and the flattening 1/13.

It is difficult to estimate at what date the crust formed a closed shell firm enough to develop stresses of a more or less permanent character when adjusting its shape to the change of the flattening. If this occurred about 1600 million years ago we shall find in this Chapter that the change of the flattening since that time is not quite sufficient to explain the shearing of the Earth's crust, even if we put its date in a recent period. JEFFREYS [1929] in his discussion of the effect of a change of rotation on the Earth's surface features, however, reckons with the possibility that the tidal friction in the earlier part of this period was greater than the computed amount and in that case the shearing of the crust may have been possible. This, moreover, is certainly the case if we put the formation of the crustal shell at an earlier date, and so we may conclude that the shearing of the crust by this cause, even at an early period of the crust's history, is not out of the question.

We may now speculate on the question of which of the two phenomena--a shift of the poles or a change of the flattening--is the most likely to have caused a disruption of the crust. Admitting the possibility of both, the fact that the stresses in the first case must have originated so much more quickly than in the second seems to be in favor of the first supposition. Assuming that the shift of the poles was caused by subcrustal currents, we may suppose this to have come about during part of a period of great tectonic activity in the crust. Taking the mean of the figures of eleven of these periods given by KUENEN [KUENEN, 1941, UMBGROVE, 1942], we find 55 million years, while the mean duration of the ten dormant periods is 120 million years. So we may expect stresses leading to the shearing of the crust to develop in a period of some 50 million years or less. For a shift of the poles over 70°, as mentioned in Chapter I, this corresponds to a velocity of the movement of about 16 cm per year, and this order of magnitude is in good agreement with the values of 19 cm and 14 cm found by LAMBERT [1922] and by WANACH [1927] for the present velocity of the polar movement. It is likely that in earlier periods of the Earth's history, when the viscosity of the subcrustal layers must have been less, the speed was even greater.

Stresses brought about by the change of the flattening must be expected to require a much longer period before they can give rise to a shearing of the crust; according to what has been said this must probably have taken at least 500 to 1000 million years. This long duration must increase the chances that the relaxation of the stresses prevents them building up to the critical value. So this argument is favorable to the first supposition. As already mentioned in Chapter I this result is in harmony with the evidence given by the topographical and geological features of the Earth's surface.

This evidence gives a slight indication that the movements of the poles have been on a smaller scale since the crustal shearing. It is easy to find a plausible cause for this. We may expect that once the crust has been broken up in separate blocks, the energy provided by eventual subcrustal currents must partly be absorbed by friction between these blocks and that less is available, therefore, for the rotation of the crust as a whole.

In this connection another speculation is, perhaps, worth-while. It might be considered likely that only since the breaking of the crust in separate blocks could great folding come into being in orogenic areas; great compressive movements in more or less limited areas may be better understood when the disruption of the crust makes possible relative movements of these blocks. This condition of the crust may explain also the complicated pattern of the tectonic axis in these areas; in most cases more than one block must have moved and the working of the shear planes must have contributed to this pattern. Lastly it is well conceivable that the crust, as long as it formed an unbroken shell, was able to resist the tectonic stresses working on it.

Taking up the main problem of the stresses and deformations of the crust caused by a shift of the poles or a change of the flattening, we shall assume the crust to have a uniform thickness over its whole surface. It is difficult to be sure about this supposition. We do not know much about the deeper layers, their physical properties, and the temperatures, so an exact treatment of the matter is out of the question. We can say, however, that the lower boundary of the rigid crust need not coincide with one of the discontinuity surfaces of density and so the data given by gravity about the depths of these surfaces have no bearing on our problem. We need not be influenced, therefore, by the fact that, according to Airy's hypothesis about isostasy, the thickness of the sialic layer must be greater in the continents than in the oceans. The results of the determinations of gravity over, and in the neighborhood of, volcanic islands show, on the contrary, that the rigid crust can not be thinner there than over the continents; the radius of the regional distribution of the isostatic compensation best fitting the gravity results in these areas is not smaller than for continental areas, and so the bending properties of the oceanic crust point to a thickness at least as great as for the continents [VENING MEINESZ, 1941 b].

Besides assuming the crust to have uniform thickness, we shall also suppose it to behave as a homogeneous, isotropic elastic body and so neglect possible differences in elastic properties. There is no doubt that such differences must be present, and so we may expect that on this account deviations from our deductions will occur.

Our problem thus is to derive the stresses and deformations in a homogeneous crustal shell of uniform thickness when it changes its shape under the effect of a shift of the poles or of a change of the flattening. Each of these phenomena causes the elements of the crustal shell to undergo small translations of which the component s_ρ normal to the crust changes the initial shape of the shell into its final figure. As the crust is obviously too weak to prevent the Earth from adopting the equilibrium figure, we can determine the shift between both figures and so consider s_ρ as given. It further is simple to see that if in our result we neglect the order of the flattening, we may assume the initial shape to be spherical. Lastly we can show that, as for both phenomena, s_ρ is only slowly variable over the Earth's surface, the bending stresses in the crust may be neglected--we shall presently return to this point and shall see that this is indeed allowable.

Starting from these assumptions, we shall now derive the equations for the stresses and deformations of a rigid spherical shell of uniform thickness of which the elements are subjected to small translations s_ρ normal to the sphere. We shall begin by leaving s_ρ undefined, substituting afterwards the values for the two cases to be investigated--the shift of the poles or the change of the flattening. Let R denote the Earth's radius, T the thickness of the crust, δ and α polar coordinates with regard to an arbitrary coordinate axis through the Earth's center, δ being the angl between this axis and the radius of the crustal element under consideration and α the angle of the plane through this radius and the axis and an arbitrary zero plane through the axis which we shall choose through the axis of rotation of the Earth, σ_δ and σ_α the normal components of the stresses working in cross sections of the crust corresponding to these coordinates, τ the shearing component of these stresses parallel to the crust, and σ_ρ the normal component of the stresses in planes parallel to the crust. We shall give positive sign to τ if, as in Figure 1, the direction of the force working in planes through the coordinate axis and acting on the crustal element at the side of increasing α is away from the axis. σ_δ, σ_α, and σ_ρ do not include the part of the stresses resulting from the hydrostatic pressure in the crust which may be assumed to have always been present; as we shall afterwards discuss, we may suppose that it has played no part in the deformations of the crust we are investigating. The assumption that the bending stresses may be neglected implies that the stresses σ_δ, σ_α, and τ are constant over the whole thickness of the crust and that the other shearing components of the stresses are zero. We likewise find that σ_ρ increases linearly with depth from a value of zero at the surface to the value, σ_r, it has at the lower boundary of the crust.

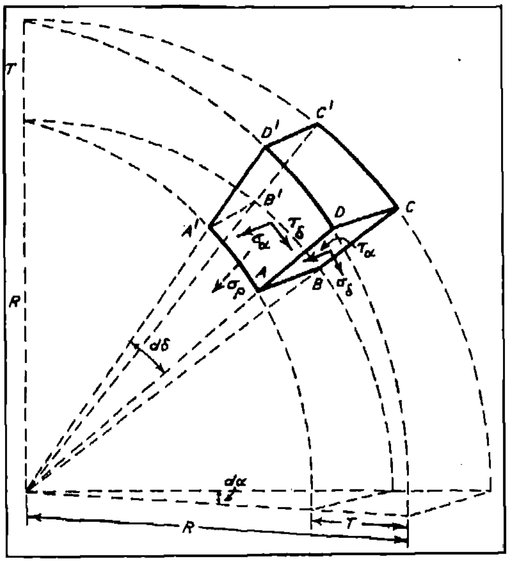


Fig. 1--Forces acting on element of spherical shell

For an elemental prism, ABCDD'A'B'C', extending over the full thickness of the crust and bounded by two planes through the coordinate axis enclosing an angle $d\alpha$ and two conic surfaces described around the axis with angles differing $d\delta$, we find the following conditions of equilibrium:

In the direction AA', $\sigma_\alpha TR \cos\delta d\delta d\alpha - (\partial\sigma_\delta/\partial\delta)TR \sin\delta d\delta d\alpha - \sigma_\delta TR \cos\delta d\delta d\alpha + (\partial\tau/\partial\alpha)TRd\delta d\alpha = 0$

In the direction AB, $(\partial\sigma_\alpha/d\alpha)TRd\delta d\alpha - (\partial\tau/\partial\delta)TR \sin\delta d\delta d\alpha - \tau TR \cos\delta d\delta d\alpha - \tau TR \cos\delta d\delta d\alpha = 0$

In the direction AD, $\sigma_r R^2 \sin\delta d\delta d\alpha + \sigma_\delta TR \sin\delta d\delta d\alpha + \sigma_\alpha TR \sin\delta d\delta d\alpha = 0$

The third terms of the first two equations are brought about by the difference in size of the surfaces ABCD and A'B'C'D'. By simplifying the three equations we derive equations (1A), (1B), and (1C).

$$(\sigma_\alpha - \sigma_\delta)\cos\delta - (\partial\sigma_\delta/\partial\delta)\sin\delta + (\partial\tau/\partial\alpha) = 0 \quad \text{(1A)}$$

$$(\partial\sigma_\alpha/\partial\alpha) - (\partial\tau/\partial\delta)\sin\delta - 2\tau\cos\delta = 0 \quad \text{(1B)}$$

$$\sigma_r + (T/R)(\sigma_\delta + \sigma_\alpha) = 0 \text{ and } \sigma_r = -(T/R)(\sigma_\delta - \sigma_\alpha) \quad \text{(1C)}$$

By applying the last formula to a layer of the crust between the surface and a depth z, we may write it $\sigma_\rho = -(z/R)(\sigma_\delta + \sigma_\alpha)$, and so we see that if σ_δ and σ_α are constant over the whole thickness of the crust, σ_ρ must indeed increase linearly with the depth z as we mentioned above.

We may likewise conclude from (1C) that σ_r is small with respect to σ_δ and σ_α; as the ratio (T/R) is less than one per cent, we may say the same of the ratio $[\sigma_r/(\sigma_\delta + \sigma_\alpha)]$. As we have already neglected quantities of the order of the flattening we may, therefore, do the same for σ_r with regard to σ_δ and σ_α.

To express the relations of the stresses and the deformations we shall introduce the translations s of the elements of the crust and its components s_δ in the direction of the great circle through the origin of the polar coordinates, s_ρ in the sense of the Earth's radius and s_α perpendicular to s_δ and s_ρ. We shall give positive sign to s_ρ if it is directed outwards and to s_δ and s_α if their directions coincide with increasing δ and α.

Neglecting σ_ρ and σ_r and introducing Young's modulus E, the shear modulus G and Poisson's coefficient m we find

$$[\sigma_\delta - (1/m)\sigma_\alpha]/E = (1/R)(\partial s_\delta/\partial\delta) + (s_\rho/R)$$

$$[\sigma_\alpha - (1/m)\sigma_\delta]/E = (s_\delta/R)\cot\delta + (1/R)(\partial s_\alpha/\partial\alpha)\operatorname{cosec}\delta + (s_\rho/R)$$

$$(\tau/G) = (1/R)[-(\partial s_\delta/\partial\alpha)\operatorname{cosec}\delta - (\partial s_\alpha/\partial\delta) + s_\alpha\cot\delta]$$

From these equations we obtain

$$\sigma_\delta - (1/m)\sigma_\alpha = (E/R)[(\partial s_\delta/\partial\delta) + s_\rho] \quad \ldots\ldots (2A)$$

$$\sigma_\alpha - (1/m)\sigma_\delta = (E/R)[s_\delta\cot\delta + (\partial s_\alpha/\partial\alpha)\operatorname{cosec}\delta + s_\rho] \quad \ldots\ldots (2B)$$

$$\tau = [mE/2(m+1)R][-(\partial s_\delta/\partial\alpha)\operatorname{cosec}\delta - (\partial s_\alpha/\partial\delta) + s_\alpha\cot\delta] \quad \ldots\ldots (2C)$$

In these equations s_ρ is given by the data of the problem. For determining the five unknown quantities σ_δ, σ_α, τ, s_δ, and s_α we dispose of the five equations (1A), (1B), (2A), (2B), and (2C) and after doing this can derive σ_r from (1C).

The solution of these equations becomes much easier for an axisymmetrical problem, as, for example, the case of a change of the flattening. In these circumstances s_α and τ are zero and the equations (1) and (2) reduce to

$$(\partial\sigma_\delta/\partial\delta) = (\sigma_\alpha - \sigma_\delta)\cot\delta \quad \ldots\ldots (3A)$$

$$\sigma_r = -(T/R)(\sigma_\alpha + \sigma_\delta) \quad \ldots\ldots (3B)$$

$$\sigma_\delta - (1/m)\sigma_\alpha = (E/R)[(\partial s_\delta/\partial\delta) + s_\rho] \quad \ldots\ldots (4A)$$

$$\sigma_\alpha - (1/m)\sigma_\delta = (E/R)(s_\delta\cot\delta + s_\rho) \quad \ldots\ldots (4B)$$

Introducing the given value of s_ρ we can derive σ_δ, σ_α, and s_δ from (3A), (4A), and (4B) and afterwards σ_r from (3B).

Assuming that the flattening β diminishes by an amount Δ and that the volume of the Earth remains the same we have (5A) for s_ρ.

$$s_\rho = \Delta R[\cos^2\delta - (1/3)] \quad \ldots\ldots (5A)$$

In this case the coordinate axis has been chosen coinciding with the axis of rotation of the Earth and so δ is the colatitude. By means of this formula for s_ρ we find the following solution of the equations (3) and (4).

$$s_\delta = -[2(m+1)/(5m+1)]\Delta R\sin\delta\cos\delta \quad \ldots\ldots (5B)$$

$$\sigma_\delta = [m/(5m+1)]\Delta E[\cos^2\delta + (1/3)] \quad \ldots\ldots (5C)$$

$$\sigma_\alpha = [m/(5m+1)]\Delta E[3\cos^2\delta - (5/3)] \quad \ldots\ldots (5D)$$

$$\sigma_r = -[4m/(5m+1)]\Delta(T/R)E[\cos^2\delta - (1/3)] \quad \ldots\ldots (5E)$$

For computing the stresses by means of these formulas we have to introduce values for the elastic constants E and m. According to GUTENBERG [1939] the bulk modulus k for the granitic layer is about 500,000 kg/cm^2 and for deeper crustal layers it is probably not far from 1,000,000 kg/cm^2. Considering these figures we shall adopt a mean value of 650,000 kg/cm^2 for the whole crust. For Poisson's coefficient m GUTENBERG [p. 358, 1939] gives slightly more than four for the granitic layer and four for the deeper continental layers, and so we shall probably be not far from the mark if we introduce a value of 4.1 for the whole crust. As we have $E = [3(m-2)/m]k$, we obtain from these figures a value of E of 1,000,000 kg/cm^2.

We shall further introduce R = 6371.2 km and a thickness T of the rigid crust of 30 km. This last value is in good agreement with the radius of the regional distribution of the isostatic compensation as derived from gravity results. This radius is given by the formula with

$$r = 2.905\,\ell \qquad (6A)$$

$$\ell = \sqrt[4]{m^2ET^3/[12(m-1)(\theta_1-\theta_0)g]} \qquad (6B)$$

and introducing the above values for E and m and putting the difference of the surface density θ_0 and the subcrustal density θ_1 at 0.6 we obtain $\ell = 80$ km. This value is in harmony with the value derived from many gravity data, as, for example, those found for Hawaii and Madeira [VENING MEINESZ, 1941 b]. The value for T, moreover, only enters in the result for σ_r; it is interesting to notice that it does not affect the values of the main stresses σ_δ and σ_α.

We have lastly to decide on the value we shall introduce for the change of the flattening, Δ. At present the flattening is 1/297 and as we have mentioned, Jeffreys determined it for 1600 million years ago at 1/210; we, therefore, shall put Δ at $[(1/210) - (1/297)] = 0.00140$.

By means of these values we shall compute the stresses and deformations given by the formulas (5). We obtain for the poles values as in (7).

$$\left.\begin{aligned} \sigma_\delta &= \sigma_\alpha = [4m/3(5m+1)]\Delta E = 356 \text{ kg/cm}^2 \\ \sigma_r &= -[8m/3(5m+1)]\Delta(T/R)E = 3.4 \text{ kg/cm}^2 \\ s_\rho &= (2/3)\Delta R = 5.9 \text{ km} \\ s_\delta &= 0 \end{aligned}\right\} \qquad (7)$$

The values of about 360 kg/cm^2 found for σ_δ and σ_α represent the maximum values of the tensional stresses occurring over the Earth's surface and we find here likewise the maximum rise of the crust, namely, 5.9 km. The value of σ_r confirms our conclusion that the stress exerted by the substratum on the crust is negligible with regard to the stresses in the crust.

For the equator we obtain

$$\left.\begin{aligned} \sigma_\delta &= [m/3(5m+1)]\Delta E = 89 \text{ kg/cm}^2 \\ \sigma_\alpha &= -[5m/3(5m+1)]\Delta E = -445 \text{ kg/cm}^2 \\ \sigma_r &= [4m/3(5m+1)]\Delta(T/R)E = 1.7 \text{ kg/cm}^2 \\ s_\rho &= -(1/3)\Delta R = -3.0 \text{ km} \\ s_\delta &= 0 \end{aligned}\right\} \qquad (8A)$$

The value of σ_α of about 450 kg/cm^2 is the maximum compression which occurs, and we have here also the maximum downward movement of the crust, namely, 3.0 km. This corresponds to a shortening of the equator of about 20 km and so this might have contributed to the shortening of the crust in the folded mountain ranges of north-south direction; the amount has originated, however, in a very long period, and so the contribution to each orogenetic period can not have been great. If, moreover, the hypothesis is true that the crust, at a very early stage of its history, was divided in blocks by a shearing process brought about by a shift of the poles, the above shortening of the equator must probably have taken place by an adjustment of the blocks along the shearing planes, and a contribution to the folding orogeny seems unlikely.

At the equator the difference of the stresses σ_δ and σ_α is maximum and, therefore, the shearing stress τ' likewise. We thus find this maximum value of the shearing stress to be

$$\tau'_m = [m/(5m+1)]\Delta E = 267 \text{ kg/cm}^2 \qquad (8B)$$

For the poles τ' is zero.

For latitude 45° we find

$$\left.\begin{aligned} \sigma_\delta &= [5m/6(5m+1)]\Delta E = 222 \text{ kg/cm}^2 \\ \sigma_\alpha &= -[m/6(5m+1)]\Delta E = -44 \text{ kg/cm}^2 \end{aligned}\right\} \qquad (9)$$

$$\left.\begin{aligned}\sigma_r &= -[2m/3(5m+1)]\Delta(T/R)E = -0.8\ \text{kg/cm}^2\\ s_\rho &= (1/6)\Delta R = 1.5\ \text{km}\\ s_\delta &= -[(m+1)/(5m+1)]\Delta R = -2.1\ \text{km}\end{aligned}\right\}\ldots\ldots\ldots(9,\ \text{conc.})$$

At this latitude the northward shift of the crust is maximum, namely, 2.1 km. The stresses and the vertical movement s_ρ are the mean here of the values at the pole and at the equator.

Examining the stresses we find, as mentioned already in Chapter I, that they are not quite sufficient in themselves to bring about a disruption of the crust; it does not seem likely that it has given way under this strain. It is, however, possible that the change of the flattening has been greater than the value we have introduced. In the first place, the tidal friction may have been stronger in the past, and in the second place, the crust may have solidified at a still earlier date and the flattening at that date must have differed more from the present value.

We have not yet investigated the way in which we may expect the crust, in case of a greater change of the flattening, to give way. We shall take up this subject at the end of this Chapter after first studying our main problem--the effect of a shift of the poles.

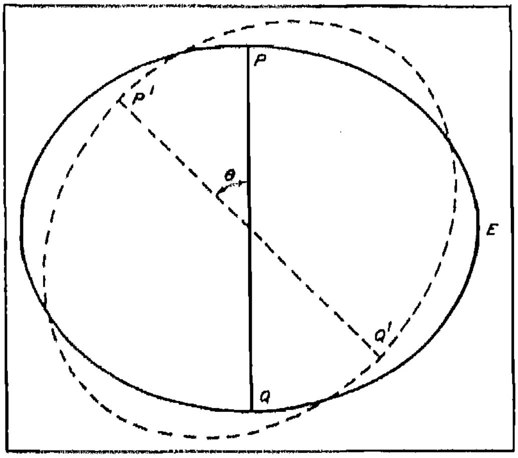


Fig. 2--Effect of shifting poles

For deriving the stresses and deformations caused by a shift of the poles we require the formula for the distance s_ρ of the crust's surface before and after the event. We assume that because of the movement of the crust around the Earth the pole after the movement coincides with the point P′ (see Fig. 2) at a distance θ from its initial position P in the crust, the angle θ being counted anti-clockwise in the Figure. The orbit described between P and P′ does not affect the following considerations; it may have been the meridian connecting both points and in this case the crust has rotated clockwise around an axis in the equator over the angle θ but it may also have been another orbit, for example, a rotation around an axis in an inclined position with regard to the plane of the equator.

Neglecting quantities of the order of the square of the flattening and denoting the latitude by φ we may represent the radius from the Earth's center to a point at the surface by $r = a(1 - \beta\ \sin^2\varphi)$ and so, supposing that the crust after the movement has adjusted itself entirely to the equilibrium figure of the Earth the shift s_ρ in the sense of the radius for points of the meridian through P and P′ is given by

$$s_\rho = \beta a[\sin^2\varphi - \sin^2(\varphi - \theta)] = \beta a \sin\theta \sin(2\varphi - \theta)\ldots\ldots\ldots\ldots\ldots(10)$$

This displacement s_ρ has its maximum value $\beta a \sin\theta$ for $\varphi = (45° + \theta/2)$ and its largest negative value $-\beta a \sin\theta$ for $\varphi = (-45° + \theta/2)$.

It is simple to prove that this deformation of the crust can be obtained by the superposition of two deformations of the kind given by (5A), namely, one with the axis coinciding with the direction $\varphi = (45° + \theta/2)$ for which $\Delta R = \beta a \sin\theta$ or, neglecting the difference of R and a, $\Delta = \beta \sin\theta$ and the second with the axis coinciding with the direction $\varphi = (-45° + \theta/2)$ for which $\Delta R = -\beta a \sin\theta$ or $\Delta = -\beta \sin\theta$. Applying (5A) and introducing successively $\delta = (\varphi - 45° - \theta/2)$ and $\delta = (\varphi + 45° - \theta/2)$ we find the following for the meridian QEP: $s_\rho = \beta R \sin\theta[\cos^2(\varphi - 45° - \theta/2) - \cos^2(\varphi + 45° - \theta/2)] = \beta R \sin\theta \sin(2\varphi - \theta)$. This is identical with (10). For the axis at right angles to this meridian plane the two deformations cancel each other, and so this is likewise in agreement to the case of a shift of the poles; this axis coincides with the axis of rotation of the crust, which does not change its length by the rotation.

This result permits a simple way of finding the solution of our problem; we can derive it from (5). For this purpose we introduce a system of polar coordinates δ, α with its axis coinciding with the axis of rotation of the crust; the origin of this system, therefore, lies in the equator. As it is shown in Figure 3, we reckon α from the great circle through the origin and the pole in its final position. The poles P_1 and P_2 of the above-mentioned systems of deformation according to (5) have latitudes of $(45° + \theta/2)$ and $(-45° + \theta/2)$ with regard to the initial position of the equator, and so their latitudes with regard to its final position are $(45° - \theta/2)$ and $(-45° - \theta/2)$; the coordinates of P_1 in the new system, therefore, are $\delta = 90°$ and $\alpha = (45° + \theta/2)$ and of P_2 are $\delta = 90°$ and $\alpha = (135° + \theta/2)$.

Introducing $\Delta = \beta \sin \theta$ in the quantities σ_m and σ_r derived from the stresses σ_δ and σ_α of (5C) and (5D) we find

$$\left.\begin{aligned} \sigma_m &= (\sigma_\delta + \sigma_\alpha)/2 = [2m/(5m + 1)]\beta E \sin \theta[(2/3) - \sin^2 \delta] \\ \sigma_v &= (\sigma_\delta - \sigma_\alpha)/2 = [m/(5m + 1)]\beta E \sin \theta \sin^2 \delta \end{aligned}\right\} \ldots\ldots\ldots\ldots (11)$$

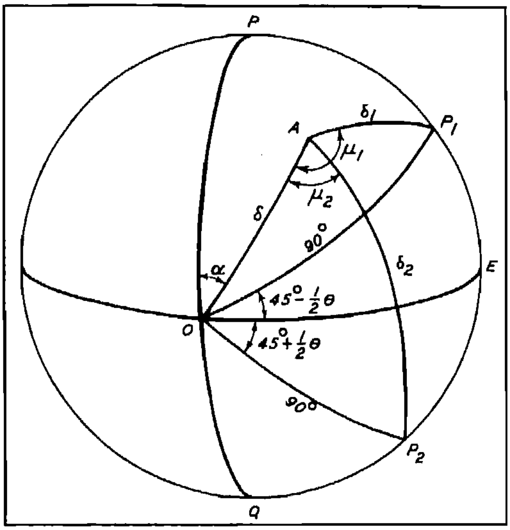


Fig. 3--System of stresses in spherical shell

This refers to the system of stresses around P_1; for the system P_2 we get the same formulas with opposite sign. The general formulas for the normal and tangential stresses working on a plane enclosing an angle μ with that of the principal stresses are $\sigma = \sigma_m + \sigma_v \cdot \cos 2\mu$ and $\tau = \sigma_v \sin 2\mu$. Introducing the denominations δ_1 and μ_1 for the system P_1 and δ_2 and μ_2 for the system P_2 as shown by Figure 3, we find σ_δ and σ_α for the combined systems P_1 and P_2 in our new coordinates as in the following formulas.

$$\sigma_\delta = -[2m/(5m + 1)]\beta E \sin \theta(\sin^2 \delta_1 - \sin^2 \delta_2) + [m/(5m + 1)]\beta E \sin \theta(\sin^2 \delta_1 \cos 2\mu_1 - \sin^2 \delta_2 \cos 2\mu_2)$$

$$\sigma_\alpha = -[2m/(5m + 1)]\beta E \sin \theta(\sin^2 \delta_1 - \sin^2 \delta_2) - [m/(5m + 1)]\beta E \sin \theta(\sin^2 \delta_1 \cos 2\mu_1 - \sin^2 \delta_2 \cos 2\mu_2)$$

$$\tau = [m/(5m + 1)]\beta E \sin \theta(\sin^2 \delta_1 \sin 2\mu_1 - \sin^2 \delta_2 \sin 2\mu_2)$$

The angles AOP_1 and AOP_2 being $(45° - \alpha + \theta/2)$ and $(135° - \alpha + \theta/2)$ we can derive

$$\left.\begin{aligned} \sin \delta_1 \sin \mu_1 &= \sin(45° - \alpha + \theta/2) \\ \sin \delta_2 \sin \mu_2 &= \sin(135° - \alpha + \theta/2) = \sin(45° + \alpha - \theta/2) \\ \sin \delta_1 \cos \mu_1 &= -\cos \delta \cos(45° - \alpha + \theta/2) \\ \sin \delta_2 \cos \mu_2 &= -\cos \delta \cos(135° - \alpha + \theta/2) = \cos \delta \cos(45° + \alpha - \theta/2) \\ \cos \delta_1 &= \sin \delta \cos(45° - \alpha + \theta/2) \\ \cos \delta_2 &= \sin \delta \cos(135° - \alpha + \theta/2) = -\sin \delta \cos(45° + \alpha - \theta/2) \end{aligned}\right\} \ldots\ldots (12)$$

Introducing this in our formulas we obtain, after some reduction,

$$\sigma_\delta = [m/(5m + 1)]\beta E \sin \theta(\sin^2 \delta + 2)\sin(2\alpha - \theta) \ldots\ldots\ldots\ldots (13A)$$

$$\sigma_\alpha = [m/(5m + 1)]\beta E \sin \theta(3 \sin^2 \delta - 2)\sin(2\alpha - \theta) \ldots\ldots\ldots\ldots (13B)$$

$$\tau = -[2m/(5m + 1)]\beta E \sin \theta \cos \delta \cos(2\alpha - \theta) \ldots\ldots\ldots\ldots (13C)$$

The value of σ_r follows from (1C)

$$\sigma_r = -[4m/(5m + 1)]\beta E(T/R)\sin \theta \sin^2 \delta \sin(2\alpha - \theta) \ldots\ldots\ldots\ldots (13D)$$

For the components of the translation s we have to combine the values of s_ρ and of the components of s_δ of the systems P_1 and P_2 as given by (5A) and (5B) in which we introduce $\Delta = \beta \sin \theta$ and $\Delta = -\beta \sin \theta$, respectively. Thus

$$s_\rho = \beta R \sin\theta(\cos^2\delta_1 - \cos^2\delta_2)$$

$$s_\delta = -[2(m+1)/(5m+1)]\beta R \sin\theta[\sin\delta_1\cos\delta_1\cos\mu_1 - \sin\delta_2\cos\delta_2\cos\mu_2]$$

$$s_\alpha = -[2(m+1)/(5m+1)]\beta R\sin\theta[-\sin\delta_1\cos\delta_1\sin\mu_1 + \sin\delta_2\cos\delta_2\sin\mu_2]$$

By using the relations of (12) these reduce to

$$s_\rho = \beta R \sin\theta \sin^2\delta \sin(2\alpha - \theta) \quad \text{(14A)}$$

$$s_\delta = [2(m+1)/(5m+1)]\beta R\sin\theta\sin\delta\cos\delta\sin(2\alpha-\theta) \quad \text{(14B)}$$

$$s_\alpha = [2(m+1)/(5m+1)]\beta R\sin\theta\sin\delta\cos(2\alpha-\theta) \quad \text{(14C)}$$

Formulas (13) and (14) give the complete solution of our problem, namely, the stresses and deformations brought about in the rigid Earth's crust by a shift of the poles over an angle θ. By introducing them in (1) and (2) we find that they indeed fulfill the conditions.

By choosing another origin for the coordinates, namely, half-way between the initial and the final position of the pole, we may obtain slightly simpler formulas, which in some cases may be useful for the investigation of our problem. They may be deduced along the same lines and do not present difficulties. Counting α with regard to the meridian through the initial and the final positions of the pole, we obtain (15) and (16).

$$\sigma_\delta = -[m/(5m+1)]\beta E\sin\theta\sin 2\delta\cos\alpha \quad \text{(15A)}$$

$$\sigma_\alpha = -[3m/(5m+1)]\beta E\sin\theta\sin 2\delta\cos\alpha \quad \text{(15B)}$$

$$\tau = [2m/(5m+1)]\beta E\sin\theta\sin\delta\sin\alpha \quad \text{(15C)}$$

$$\sigma_r = [4m/(5m+1)]\beta E(T/R)\sin\theta\sin 2\delta\cos\alpha \quad \text{(15D)}$$

$$s_\rho = -\beta R\sin\theta\sin 2\delta\cos\alpha \quad \text{(16A)}$$

$$s_\delta = -[2(m+1)/(5m+1)]\beta R\sin\theta\cos 2\delta\cos\alpha \quad \text{(16B)}$$

$$s_\alpha = [2(m+1)/(5m+1)]\beta R\sin\theta\cos\delta\sin\alpha \quad \text{(16C)}$$

Before discussing our formulas and drawing conclusions we have to consider a point in connection with the assumptions from which we started our deductions; we have to prove that we were justified in neglecting the bending stresses in the crust. For this investigation we shall choose the bending of the meridian along which the pole has moved. The radius of curvature of the meridian is given by $\rho_m = a(1 - e^2)(1 - e^2\sin^2\varphi)^{-3/2}$ where $e^2 = (2\beta - \beta^2)$. If we indicate the variation of ρ_m caused by the deformation of the crust by Δ_ρ, the stress σ_f which because of the bending originates at the outer edge of a cross-section of the crust is

$$\sigma_f = (1/2)\Delta_\rho(T/\rho_m^2)E$$

Neglecting quantities of the order of the flattening we may substitute for ρ_m the mean Earth's radius R and for Δ_ρ

$$(\partial\rho_m/\partial\varphi)\theta = 3\beta R\theta\sin 2\varphi$$

We thus obtain

$$\sigma_f = (3/2)\beta E(T/R)\theta\sin 2\varphi \quad \text{(17)}$$

This stress is of the same order of magnitude as σ_r and we have already argued that because of the smallness of the ratio (T/R) we may neglect it with regard to the main stresses σ_δ and σ_α.

For (5) in the case of a change of the flattening the same is true. The variation of ρ_m in this case is given by

$$(\partial\rho_m/\partial\beta) = -2a[1 - (3/4)\sin^2\varphi]$$

and so

$$\Delta_\rho = 2\Delta R[1 - (3/4)\sin^2\varphi]$$

and

$$\sigma_f = \Delta E(T/R)[1 - (3/4)\sin^2\varphi] \quad \text{(18)}$$

Comparing this with (5E) we see that again σ_f is of the order of σ_r and that we may neglect it with regard to σ_δ and σ_α.

Returning to the case of a shift of the pole we shall now examine the stresses that are brought about by it. For this purpose we shall use (13) based on an origin of the coordinates in the equator at a point coinciding with the axis of rotation of the crust. Equations (13A) and (13B) show that in two great circles through this origin given by $\alpha = \Theta/2$ and by $\alpha = (\Theta/2 + 90°)$ the stresses σ_δ and σ_α disappear and we have pure shear. According to (13C) the shearing stress τ in these circles is maximum at the origin where the two circles intersect at right angles. The value τ_m of this maximum is

$$\tau_m = [2m/(5m + 1)]\beta E \sin \Theta \ldots\ldots\ldots\ldots (19)$$

Assuming the value of Θ of the shift of the pole to be 90°, which gives a maximum value of the deformation and the stresses, and introducing the values already adopted of $m = 4.1$ and $E = 1{,}000{,}000$ kg/cm^2, we find when using β at its present value of (1/297), $\tau_m = 1290$ kg/cm^2. This shearing stress is considerable and we may well imagine the crust to give way under its effect. In case the phenomenon has occurred at a very early date of the Earth's history it must even have been larger because the flattening must have been greater at that time. Using the value of flattening as (1/210) which Jeffreys derived for a date 1600 million years ago, we find $\tau_m = 1820$ kg/cm^2.

For the two great circles through the origin of the coordinates which bisect the right angles between the former pair and for which we, therefore, have $\alpha = (45° + \Theta/2)$ and $\alpha = (-45° + \Theta/2)$ we conclude from (13C) that τ disappears. The same is true for $\delta = 90°$, namely, for the meridian along which the pole has moved. For this meridian we further find that everywhere $\sigma_\delta = 3\sigma_\alpha$, a result which we also may find at once by examining (15A) and (15B). σ_δ is here the normal stress in the meridian cross-section of the crust. The maximum absolute values of σ_δ are found in the crossings of this meridian with the two great circles, that is, for $\delta = 90°$ and $\alpha = (45° + \Theta/2)$ or $\alpha = (-45° + \Theta/2)$; for the first it is a maximum tension and for the second a maximum compression. Their absolute values in both cases amount to

$$\sigma_{\delta m} = [3m/(5m + 1)]\beta E \sin \Theta \ldots\ldots\ldots\ldots (20)$$

and for $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, $\Theta = 90°$, and $\beta = (1/297)$ this gives $\sigma_{\delta m} = 1930$ kg/cm^2. For $\beta = (1/210)$ we obtain $\sigma_{\delta m} = 2720$ kg/cm^2. We see again in this case that the stresses σ_δ and σ_α, as well as τ, do not depend on the thickness of the rigid crust; according to (13D) this only enters in the computation of the pressure σ_r exerted on the crust by the substratum.

In the crossings of the meridian $\delta = 90°$, where we found that τ is zero with the two great circles $\alpha = \Theta/2$ and $\alpha = (\Theta/2 + 90°)$ in which we saw that σ_δ and σ_α disappear, we have two points where all the stresses are zero. These points, therefore, are entirely free from stress.

Lastly it may be mentioned that from (13) we can conclude that the system of stresses has five planes of symmetry, namely, the meridian $\delta = 90°$ and the four great circles through the origin, $\alpha = (\Theta/2 - 45°)$, $\alpha = \Theta/2$, $\alpha = (\Theta/2 + 45°)$, and $\alpha = (\Theta/2 + 90°)$.

From our examination of the stresses it follows that probably the crust can not resist the stresses caused by a shift of the poles over a large angle. We have now to consider the question of how the crust will give way and along which lines we may expect this to occur. According to the theory of Mohr the break must take place in the cross-sections of maximum shear and in every point two such planes are present at right angles to each other. A newer theory of BYLAARD [1935, 1939] bearing on plastic deformation, since adopted also by VAN ITERSON [1943] supposes likewise two planes in each point, but these planes enclosing angles depending on the stresses. As the topography in many areas shows two predominating directions under angles different from 90° it seems likely that this last theory agrees better with the conditions in the Earth's crust. Bylaard himself has already brought it to bear on crustal problems and has given arguments for its validity in this case. He points out that although the materials of the crust at the surface are brittle, the great pressure in the major part of the crust must prevent the surpassing of the cohesion of the crystals, and that thus the deformation will take place by shear through the crystals and at higher values of the stresses; it thus must have a plastic character. As plastic deformation is characterized by conditions of flow the coefficient of Poisson in these parts may be expected to have a value of two.

Bylaard's theory on plastic deformation in elastic media is based on the supposition that in a thin plate on which only forces in its own plane are acting, plastic flow by preference must occur in a band of which in the length direction the dimensions are not changed, because otherwise the connection with the adjoining material would be severed and this would absorb a great deal of energy. Denoting the normal component of the stress in cross-sections of the plate parallel to the band by σ and at right angles to it by σ' and indicating the change in length per unit of length in both senses by ϵ and ϵ', Bylaard's condition amounts to $\epsilon' = 0$, which may be written $(1/E)(\sigma' - \sigma/2) = 0$, or

$$\sigma' = (1/2)\sigma \qquad (21)$$

By means of the well-known relations we shall express σ and σ' in the principal stresses ρ_1 and ρ_2 and in the angle ψ enclosed between the band and the cross-section in which ρ_1 acts. Introducing

$$\rho_m = (1/2)(\rho_1 + \rho_2) \text{ and } \rho_v = (1/2)(\rho_1 - \rho_2) \qquad (22A)$$

we have

$$\left.\begin{aligned} \sigma &= \rho_m + \rho_v \cos 2\psi \\ \sigma' &= \rho_m - \rho_v \cos 2\psi \end{aligned}\right\} \qquad (22B)$$

and (21) becomes

$$(1/2)\rho_m - (3/2)\rho_v \cos 2\psi = 0$$

or

$$\cos 2\psi = (\rho_m/3\rho_v) = [(\rho_1 + \rho_2)/3(\rho_1 - \rho_2) \qquad (22C)$$

Bylaard often writes this condition in the equivalent form

$$\tan\psi \quad \sqrt{(1 - \cos 2\psi)/(1 + \cos 2\psi)} = \sqrt{(3\rho_v - \rho_m)/(3\rho_v + \rho_m)} = \sqrt{(\rho_1 - 2\rho_2)/(2\rho_1 - \rho_2)} \qquad (22D)$$

Formulas (22C) or (22D) give the direction in which plastic flow will take place. For the case of pure shear, that is, when $\rho_2 = -\rho_1$ the angle ψ is $\pm 45°$, and so in this case Bylaard's theory coincides with that of Mohr; the plastic deformation occurs in the two planes of maximum shear. In other conditions, ψ assumes other values and the two theories diverge; in all cases, however, we find two values for ψ--one with positive sign and another of the same absolute value with negative sign. So in each point we obtain two planes of plastic deformation in symmetrical positions with regard to the planes of principal stress.

Van Iterson has extended Bylaard's theorem to the three-dimensional case. Maintaining the condition that the direction of the band in which plastic deformation occurs is such that it does not change its length we find the following formulas. When indicating the third principal stress by ρ_3, (21) becomes

$$\sigma' = (1/2)\sigma + (1/2)\rho_3 \qquad (23)$$

and (22C) becomes

$$\cos 2\psi = [(\rho_1 + \rho_2 - 2\rho_3)/3(\rho_1 - \rho_2)] = [(\rho_1 - \rho_3) - (\rho_3 - \rho_2)]/3(\rho_1 - \rho_2) \qquad (24A)$$

so (22D) changes to

$$\tan\psi \quad \sqrt{(\rho_1 - 2\rho_2 + \rho_3)/(2\rho_1 - \rho_2 - \rho_3)} = \sqrt{[(\rho_1 - \rho_2) - (\rho_3 - \rho_2)]/[(\rho_1 - \rho_2) + (\rho_1 - \rho_3)]}. \qquad (24B)$$

By writing the formulas in this way Van Iterson shows that ψ only depends on the differences of the principal stresses and not on their absolute values. This result sounds plausible; Bylaard has likewise pointed out that the superposition of an equal pressure in all directions may not be expected to affect the way in which plastic flow sets in. This is important for our problems regarding the Earth's crust; it makes it probable that the hydrostatic pressure in the crust does not influence the phenomena except in enforcing the plastic character of the deformation.

Van Iterson supposes that in general the planes of plastic flow must be parallel to the direction of the middle of the three principal stresses, or, in the terms of our formulas, that ρ_3 is the middle stress. There can be no doubt that in case the dimensions of the body are about the same in all directions this must be true. If we make use of the usual way of representing the stresses in the three-dimensional case by three circles (see Fig. 4), we see at once that the greatest shear is indicated by the circle belonging to the greatest and the smallest principal stresses, and so we may expect that plastic flow will occur in planes of which the position and the stresses are indicated by this circle, that is, in planes through the axis of the middle stress.

For the deformations of a plate of which the thickness is small with regard to the other dimensions, it seems probable that this may no longer be allowed. If Bylaard's supposition is valid, the condition of the dimension remaining the same must evidently be applied to directions in the plane of the plate, and so ρ_1 and ρ_2 in (24) must retain their meaning of indicating the stresses in normal cross-sections of the plate independent of their being or not being the greatest and smallest principal stresses; it is not necessary that the value of ρ_3 perpendicular to the plate lie between the values of ρ_1 and ρ_2. We shall see, for example, that for the stress conditions in the Earth's crust which we are investigating this is not everywhere the case. The question then arises whether in that case the plane of flow, which we know goes through the direction given by (24), may be expected to be perpendicular to the plate.

Dealing with this problem it is in general not possible to apply the same hypothesis of Bylaard for this direction and to suppose that the plastic flow will occur in a plane of which the dimensions in this sense likewise do not change; for an arbitrary stress situation there are no planes remaining entirely undeformed. We can think of two other suppositions instead, both of which we shall investigate. In the first place, we may suppose that in this sense the plane will be so situated that the shearing stress is a maximum, and in the second place, we may replace Bylaard's supposition of the dimensions remaining the same by a more general formula on the same base which can be fulfilled, namely, by the condition that the energy required in the boundary zone between the plastic and elastic areas must be a minimum. For thin plates, this last hypothesis must, no doubt, practically come to the same as the condition that in the direction of the plate the dimensions must remain unaltered; in a sense at right angles the plane must adjust itself so that

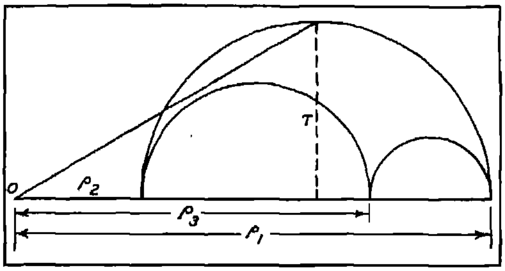


Fig. 4--Graphical presentation of stresses in three-dimensional case

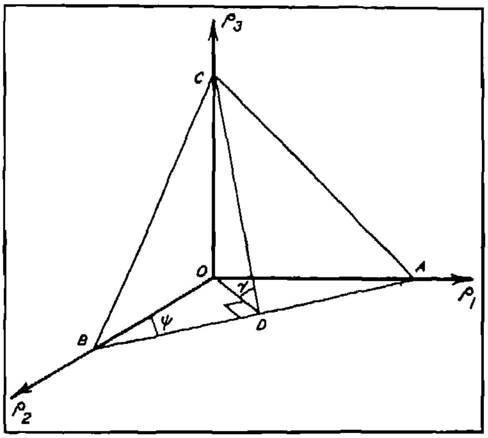


Fig. 5--Shear in plane cutting horizontal plane

the energy is a minimum. We shall see that both suppositions lead to the possibility of planes of shear not normal to the plate. For the Earth's crust the formation of inclined planes has its consequences; it must lead to vertical movements on both sides of the shear. If there is compression in this plane, this must in itself give rise to such movements, and in case of tension vertical movements must be brought about by the readjustment of the isostatic balance.

For investigating the hypothesis of maximum shear we shall first derive the formula for the shear in an arbitrary plane in the direction given by (24). In Figure 5 the three axes represent the directions of the stresses ρ_1, ρ_2, and ρ_3, AOB represents the plane of the plate, the angle OBA represents the angle ψ given by (24A) or (24B), and AB, therefore, is a line of flow. ABC is an arbitrary plane through AB making an angle γ with the plane of the plate. We want to determine the shearing stress $\tau_{\psi\gamma}$ in this plane.

The normal to ABC makes angles α, β, and γ with the directions ρ_1, ρ_2, and ρ_3. According to the well-known trigonometrical formula we have $\cos\alpha = \sin\gamma\cos\psi$ and $\cos\beta = \sin\gamma\sin\psi$, and so the three components, parallel to the axis, of the stress working on ABC are $\rho_1\sin\gamma\cos\psi$, $\rho_2\sin\gamma\sin\psi$, and $\rho_3\cos\gamma$. Determining the two components of $\tau_{\psi\gamma}$, namely, τ_{AB} in the direction of AB and τ_{cd} in the direction of the perpendicular CD on AB we find

$$\tau_{AB} = (\rho_1 - \rho_2)\sin\psi\cos\psi\sin\gamma = [(\rho_1 - \rho_2)/2]\sin 2\psi\sin\gamma$$

$$\tau_{CD} = (\rho_1\cos^2\psi + \rho_2\sin^2\psi - \rho_3)\sin\gamma\cos\gamma = (1/2)\{(\rho_1 + \rho_2)/2 + [(\rho_1 - \rho_2)/2]\cos 2\psi - \rho_3\}\sin^2\gamma$$

and by means of (24A)

$$\tau_{CD} = (1/3)(\rho_1 + \rho_2 - 2\rho_3)\sin^2\gamma$$

This gives

$$\tau^2_{\psi\gamma} = (1/4)(\rho_1 - \rho_2)^2\sin^2 2\psi\sin^2\gamma + (1/9)(\rho_1 + \rho_2 - 2\rho_3)^2\sin^2 2\gamma$$

and using (24A)

$$\tau^2_{\psi\gamma} = [(1/4)(\rho_1 - \rho_2)^2 - (1/36)(\rho_1 + \rho_2 - 2\rho_3)^2] \sin^2\gamma + (1/9)(\rho_1 + \rho_2 - 2\rho_3)^2 \sin^2 2\gamma \ldots (25)$$

By differentiating this with regard to γ and equating the result to zero we find that the maximum value $\tau_{\psi\gamma m}$ of the shear occurs for

$$\cos 2\gamma = (1/16)\left\{1 - 9[(\rho_1 - \rho_2)/(\rho_1 + \rho_2 - 2\rho_3)]^2\right\} \ldots\ldots\ldots\ldots (26A)$$

which may also be written

$$\cos 2\gamma = -(1/16)\tan^2 2\psi \ldots\ldots\ldots\ldots (26B)$$

The corresponding value of the maximum shear is

$$\tau_{\psi\gamma m} = (1/16)\left\{5 + 3[(\rho_1 - \rho_2)/(\rho_1 + \rho_2 - 2\rho_3)]^2\right\}(\rho_1 + \rho_2 - 2\rho_3) \ldots (27A)$$

or

$$\tau_{\psi\gamma m} = (1/3)(\rho_1 + \rho_2 - 2\rho_3)\sin^2\gamma \ldots\ldots\ldots\ldots (27B)$$

Examining (26B) we see that for $\psi >$ arc tan 4, that is, for $\psi > 75°58'$ the maximum is no longer real, and so for these values of ψ the greatest value of $\tau_{\psi\gamma}$ is found for $\gamma = 90°$, that is, for normal cross-sections of the plate. By introducing this in (25) we obtain the maximum shear in this case.

$$\tau_{\psi\gamma m} = \sqrt{(1/4)(\rho_1 - \rho_2)^2 - (1/36)(\rho_1 + \rho_2 - 2\rho_3)^2} = (1/2)(\rho_1 - \rho_2)\sin 2\psi \ldots (28)$$

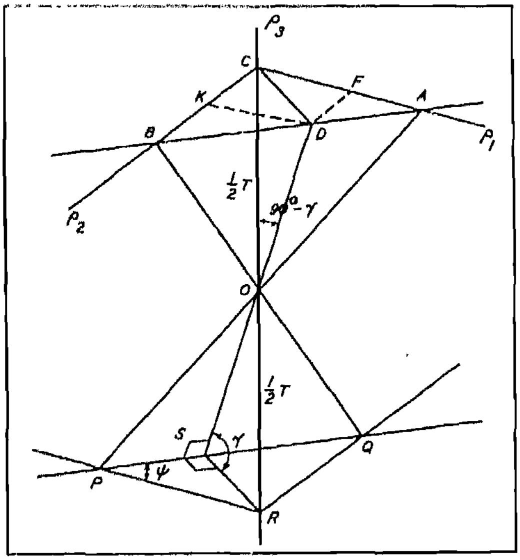


Fig. 6--Diagram of plane of flow

So we find that only for values of ψ between 45° and 38° the plate will shear along normal cross-sections. Table 1 shows some values of γ for smaller values of ψ.

According to the second hypothesis the plane of flow adjusts itself in such a way that the energy required in the boundary zone between the plastic and elastic areas is minimum. If the plane ABC of Fig. 6 represents the upper and PQR the lower surface of the crust, O a point on the ρ_3 axis in the middle of the crust (OC = OR = T/2), PQOAB the plane of flow, and SD as well as CD perpendicular to AB, we may suppose this energy to be proportional to the surface of the plane of flow between AB and PQ, that is, to SD, and also to the square of the component in PQOAB of the displacement of D with regard to O. Denoting this displacement by Δ and its components in the sense of the ρ_1, ρ_2, and ρ_3 axis by Δ_1, Δ_2, and Δ_3, we have

$$\left.\begin{aligned} E\Delta_1 &= [\rho_1 - (1/2)\rho_2 - (1/2)\rho_3] \times KD = (1/2)T[\rho_1 - (1/2)\rho_2 - (1/2)\rho_3]\cos\psi\cot\gamma \\ E\Delta_2 &= [\rho_2 - (1/2)\rho_1 - (1/2)\rho_3] \times FD = (1/2)T[\rho_2 - (1/2)\rho_1 - (1/2)\rho_3]\sin\psi\cot\gamma \\ E\Delta_3 &= (1/2)T[\rho_3 - (1/2)\rho_1 - (1/2)\rho_2] \end{aligned}\right\} \ldots (29)$$

If Δ_γ indicates the component of Δ in the plane OAB, we obtain by making use of these formulas and of (24A)

$$\Delta^2_\gamma = (9/64)(T^2/E^2)(\rho_1 - \rho_2)^2 \sin^2 2\psi \cot^2\gamma + (1/16)(T^2/E^2)(\rho_1 + \rho_2 - 2\rho_3)^2(\cos^2 2\gamma/\sin^2\gamma) \ldots\ldots\ldots\ldots (30)$$

By multiplying this by SD = T cosec γ and using (24A) again, we find that the energy mentioned above must be proportional to

$$T\Delta^2_\gamma \operatorname{cosec} \gamma = (1/64)(T^3/E^2)(\rho_1 + \rho_2 - 2\rho_3)^2[16 \sin \gamma - (16 + \tan^2 2\psi)(1/\sin \gamma) + (4 + \tan^2 2\psi)(1/\sin^3\gamma)] \quad (31)$$

So our problem reduces to finding the value of γ which renders the last factor a minimum. By differentiating with regard to γ and equalling to zero we thus obtain

$$\sin^2 \gamma = -(1/2)[1 + (1/16) \tan^2 2\psi] + (1/2)\sqrt{[1 + (1/16) \tan^2 2\psi]^2 + 3[1 + (1/4) \tan^2 2\psi]} \quad (32)$$

It is simple to prove that this gives indeed a minimum value of the energy.

By introducing $\sin \gamma = 1$ we find the maximum value of ψ providing a real solution; we thus obtain $\tan^2 2\psi = 10$ and $\psi = 36°14'$. For all values of ψ between 45° and this limit the minimum energy is given by $\gamma = 90°$ or, in other words, the planes of flow according to our supposition must be normal to the crust. For all smaller values of ψ we get inclined planes.

Some results are given in Table 1 by (24A), (26A), and (32) for different values of the ratio $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$. The first line contains the corresponding values of ψ, the second the values of γ_1 as given by (26A) for the hypothesis of maximum shear, and the third the values of γ_2 as provided by (32) for the last hypothesis.

Table 1--Values of ψ, γ_1, and γ_2 for various values of ratio $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$ computed from (24A), (26A), and (32)

Computed value	For $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$ equal to						
	1/2	2/3	5/6	1	7/6	4/3	3/2
	° ′	° ′	° ′	° ′	° ′	° ′	° ′
ψ	45 00	41 49	38 44	35 16	31 48	28 08	24 06
γ_1	90 00	90 00	90 00	60 00	52 21	49 02	47 14
γ_2	90 00	90 00	90 00	74 20	60 10	53 55	50 14

We see that the results of the two hypotheses do not differ much; in both cases the planes of flow are inclined with regard to the plane of the plate in case ψ is below a certain limit, 38° in the first case and 36°14′ in the second. It is not possible to make sure which of the two hypotheses is nearer to the truth, but if the shear planes in the Net obey the formula of Bylaard, as seems to be the case for the Earth's crust, it appears reasonable to prefer the second, which is in better harmony with Bylaard's hypothesis than the first. Only experimental evidence for different values of the ratio $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$ can give us basis for a sound decision on this matter; in this way only we may hope to obtain an answer to the question whether one of the two hypotheses can be adopted. As Van Iterson indicated to the writer in connection with the extensive investigation he has made on the subject of plastic deformation, the problem is extremely complicated and far from ripe for a final settlement. For the phenomena in the Earth's crust an additional difficulty arises from the circumstance that relative vertical movements on both sides of the shear plane, as they may be expected for an inclined plane, must bring about flow in the plastic substratum. This will absorb energy and it might, therefore, be possible that this change of the conditions also affects the course of events. It is clear that for the areas where under all circumstances normal planes may be expected, this complication is not present nor is there any uncertainty about the position of the plane.

We shall now apply our results to the problems of the Earth's crust, in the first place to the stresses caused by a shift of the pole. For this purpose we have to derive the principal stresses and the corresponding planes. We know that ρ_3 acting on planes parallel to the plate is zero. For deducing ρ_1 and ρ_2 we shall use (13). The angle μ between the direction of ρ_1 and the great circle through the origin of the coordinates belonging to these formulas--the point where the axis around which the crust has rotated cuts the equator--is given by

$$\tan 2\mu = 2\tau/(\sigma_\delta - \sigma_\alpha) = -[2 \cos \delta/(1 + \cos^2 \delta)] \cot(2\alpha - \theta) \quad (33)$$

By means of this value of μ we can derive ρ_1 and ρ_2 from

$$\left.\begin{aligned} \rho_1 &= (\sigma_\delta + \sigma_\alpha)/2 + [(\sigma_\delta - \sigma_\alpha)/2] \sec 2\mu \\ \rho_2 &= (\sigma_\delta + \sigma_\alpha)/2 - [(\sigma_\delta - \sigma_\alpha)/2] \sec 2\mu \end{aligned}\right\} \quad (34)$$

Introducing these values in (24A) and using (13A), (13B), and (13C) we obtain

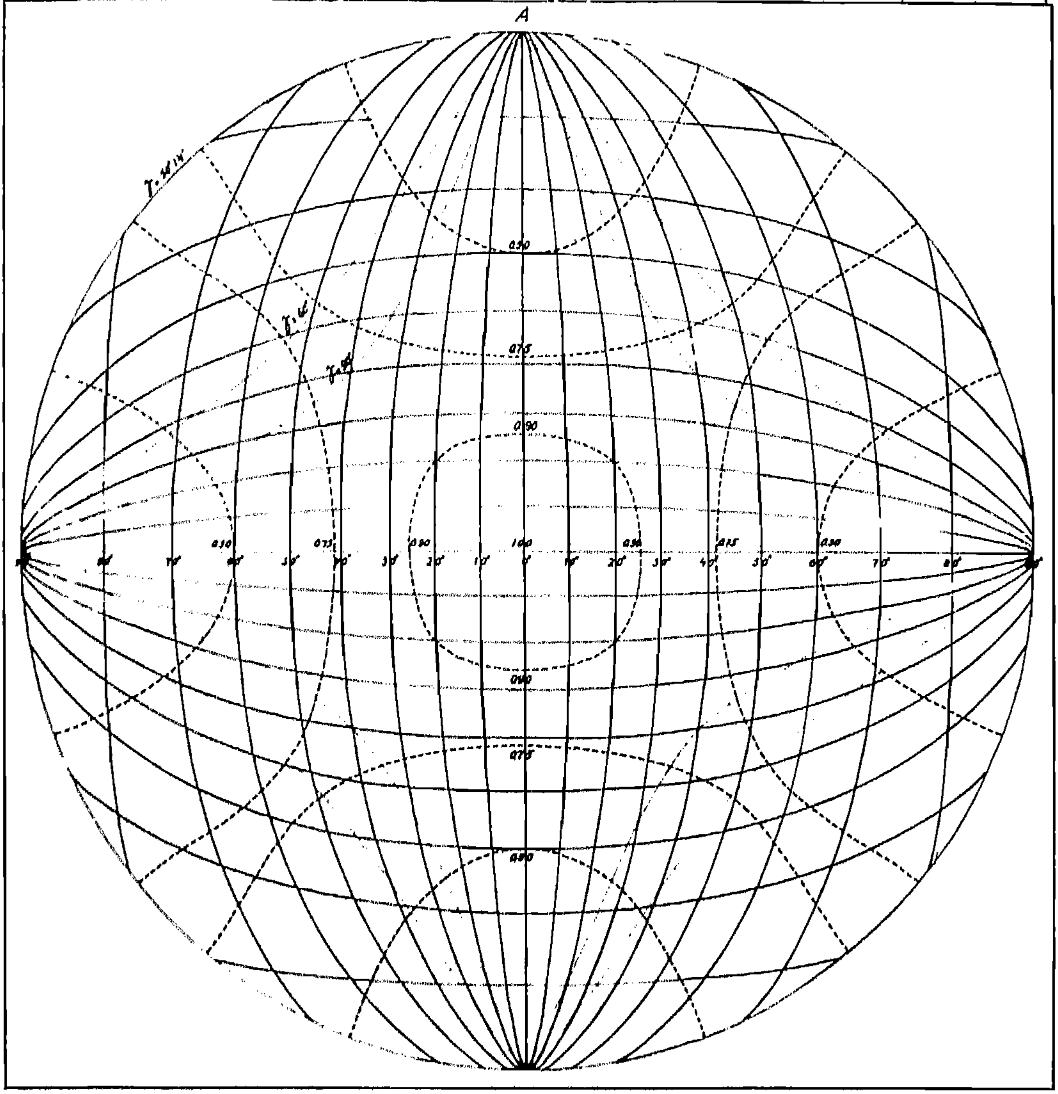


Fig. 7--Shear pattern in stereographic projection of the half sphere for infinitesimal shift of the poles; for shift over the angle θ the figure has to be rotated clockwise over $\theta/2$. The dashed lines indicate shear intensity; the dotted lines the possible angle of the shear planes with the crust

$$\cos 2\psi = (1/3)[(\sigma_\delta + \sigma_\alpha)/(\sigma_\delta - \sigma_\alpha)] \cos 2\mu = (2/3)[\sin^2 \delta /(1 + \cos^2 \delta)] \cos 2\mu \, . . \quad (35)$$

If ψ represents the positive angle corresponding to this formula, the angles between the two planes of shear and the great circle through the origin are $(\mu + \psi)$ and $(\mu - \psi)$. So (33) and (35) provide us with the position of the planes of shear in each point. Figure 7 gives the results of the computations for a half sphere around the origin of the coordinates. It has been drawn in stereographic projection, and the pole is found on the circumference at an angular distance of $\theta/2$ to the left of the point A; to bring it in the normal position with horizontal equator the Figure, therefore, must be turned clockwise over an angle $\theta/2$. In the position of Figure 7 the angle $(\alpha - \theta/2)$ is counted clockwise from the radius through A.

From (33) and (35) it follows that Figure 7 has four axes of symmetry, namely, $(\alpha - \theta/2) = -45°, 0°, 45°$, and $90°$; this corresponds to the axis mentioned above regarding the stresses. We further find that for $(\alpha - \theta/2) = 0°$ or $90°$, $\mu = 45°$ and $\psi = 45°$ and $(\mu + \psi) = 90°$ and $(\mu - \psi) = 0°$. For $(\alpha - \theta/2) = \pm 45°$ we have $\mu = 0°$ and $\cos 2\psi = (2/3)[\sin^2 \delta/(1 + \cos^2 \delta)$. For $\delta = 90°$ independent of α, $\mu = 90°$, $\cos 2\psi = (2/3)$, and $\psi = 24°06'$; and $(\mu + \psi) = 114°06'$ and $(\mu - \psi) = 65°54'$.

So in the meridian, at the border of the Figure, the angles the two shear directions make with the radius towards O are everywhere $\pm$ 65°54′.

By means of the results given by (33) and (35) for $(\mu + \psi)$ and $(\mu - \psi)$, in a good many points two systems of curves have been drawn in Figure 7 representing the shear curves over the Earth's surface. These systems show four singular points, namely, A, B, C, and D, where the curves converge. The value of ψ at these points is indeterminate; this corresponds to the stresses being zero there.

Two other systems of curves have been drawn in Figure 7. In the first place we find the stippled curves which connect the points where, according to the second hypothesis, the inclination γ of the shear planes with regard to the plane of the crust is 60° or 90°; in the area inside the last curves we have $\gamma = 90°$, and so here the shear planes are everywhere normal to the crust. These curves have been derived by means of (32) and a formula expressing ψ in δ and α, which may be derived from (33) and (35). By making use of (15A), (15B), and (15C) instead of (13A), (13B), and (13C) it is easy to prove that these curves are characterized by the property that at an arbitrary point E the angle ψ as well as the angle between the great circles connecting E with A and B are constant along the same curve. The last angle is halved by the direction of the principal stresses in E.

In the second place we have the broken curves connecting the points where the critical stress is equal to 90 per cent, 75 per cent, and 50 per cent of the maximum value found at O. For these deductions we have adopted the hypothesis of HUBER [1904] and HENCKY [1924], according to which the plastic flow begins to occur when the stress σ_v given by

$$\sigma_v^2 = (1/2)[(\rho_1 - \rho_2)^2 + (\rho_2 - \rho_3)^2 + (\rho_1 - \rho_3)^2] \quad \ldots\ldots\ldots\ldots (36A)$$

surpasses a certain critical value. For our case we have $\rho_3 = 0$, and so we obtain

$$\sigma_v^2 = \rho_1^2 - \rho_1\rho_2 + \rho_2^2 = (1/4)(\rho_1 + \rho_2)^2 + (3/4)(\rho_1 - \rho_2)^2 \quad \ldots\ldots\ldots (36B)$$

Introducing in this formula the stresses σ_δ, σ_α, and τ instead of ρ_1 and ρ_2 we find

$$\sigma_v^2 = (1/4)(\sigma_\delta + \sigma_\alpha)^2 + (3/4)(\sigma_\delta - \sigma_\alpha)^2 + 3\tau^2$$

and by means of (13A), (13B), and (13C)

$$\sigma_v^2 = \left\{[m/(5m + 1)]\beta E \sin\theta\right\}^2 [7 \sin^4\delta \sin^2(2\alpha - \theta) + 12 \cos^2\delta] \quad \ldots\ldots\ldots (37)$$

The first factor is constant over the Earth's surface, and the second variable factor attains a maximum value of 12 for $\delta = 0$, that is, for the origin 0 of the coordinates in Figure 7. So σ_v attains its maximum σ_{vm} at this same point. The ratio of σ_v in an arbitrary point to this maximum is

$$\sigma_v/\sigma_{vm} = \sqrt{(7/12)\sin^4\delta \sin^2(2\alpha - \theta) + \cos^2\delta} \quad \ldots\ldots\ldots\ldots (38)$$

The dotted curves of Figure 7, representing values of 90 per cent, 75 per cent, and 50 per cent of this ratio have been computed by means of this formula. They give an idea about the parts of the Earth's crust that must first be liable to plastic flow along the curves of the Net. Inside the curve for 50 per cent it seems less likely that plastic deformation has taken place.

The maximum value of the critical stress at O is given by

$$\sigma_{vm} = [m\sqrt{12}/(5m + 1)]\beta E \sin\theta \quad \ldots\ldots\ldots\ldots (39)$$

and introducing the values of page 10: $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, $\theta = 90°$, and $\beta = (1/297)$ we find $\sigma_{vm} = 2230$ kg/cm^2 and for $\beta = (1/210)$, $\sigma_{vm} = 3150$ kg/cm^2. These values confirm our viewpoint that probably the crust can not have borne the stresses without giving way; they exceed the limits we may expect to be valid for the crustal materials.

By means of Figure 7 we can determine the Net of shear curves over the Earth's surface for each value of θ. Choosing the corresponding situation of P we may draw the net of meridians and parallels in stereographic projection and we are free to give the point O any longitude we wish. If this geographic net is sufficiently dense it is easy to change over to another projection; we have simply to transfer the points of intersection of the shear curves with the meridians and parallels and the curves can be drawn. Net 1 has been done on a Mercator projection. In order to adjust the directions of the shear curves as well as possible to the prevalent directions of topography of the North Atlantic in azimuths of about 65° west and 45° east [VENING MEINESZ, 1942], the value of θ has been fixed at 70° and the longitude of O at 0° Greenwich. This last choice allows a range of not much more than 10° without injuring the correlation. It is simple to check this by moving Net 1 with regard to the map in a horizontal sense. For the angle θ the correlation is even more sensitive; a rotation of Figure 7 over 5° clearly lessens it. The azimuth of the bisector of the angle between the two directions in the North Atlantic adopted at 10° is undoubtedly greater than 5° and smaller than 15°.

It might well be possible that, since the breaking catastrophe of the crust, it has further moved around the Earth. In fact, it is likely that the forces causing the motion up to that moment have continued to work. We have two possibilities in this connection--either these forces have again been able to move the crust as a whole or this has not been the case. The latter possibility might be explained by the supposition that the energy for moving the systems of blocks into which the crust has been divided is larger than for the unbroken crust because of the friction between the blocks. Especially if we assume that the movement has been brought about by subcrustal currents, we may expect a strong tendency towards differential motion of the blocks, and so the latter possibility does not seem unlikely. If, however, the crust has continued to move, the pole must have undergone a contrary motion with regard to the crust of the same size. The component φ_1 of this movement in the sense of the border meridian of Figure 7 alters the angle POA and so, for a certain value of this angle derived from the topographic evidence, the angle θ described before the catastrophe must have been so much less that

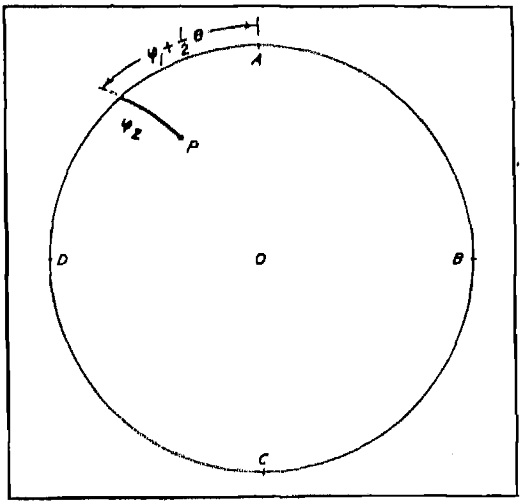


Fig. 8--Position of pole outside border meridian

$$\text{Angle POA} = \varphi_1 + \theta/2 \quad \ldots \quad (40A)$$

If there has been a component φ_2 of the motion at right angles to the border meridian, the pole has reached a position outside the border meridian as indicated in Figure 8. The geographic net of meridians and parallels in stereographic projection through P can be constructed as before, and we may again transfer Figure 8 to Mercator projection. Net 2 shows the result thus obtained for $\varphi_2 = 10°$. As is shown in the next paragraph, we find that the correlation to the topography of this Net is less than for Net 1, and if we repeat the procedure with $\varphi_2 = -10°$, that is, with a motion of the pole in the opposite sense, we find it still worse. So it appears probable that there has been no appreciable movement of the pole in this sense after the crustal breaking.

Summarizing, we find that a movement φ of the pole after the catastrophe is possible but that it must have occurred mainly in the same great circle as before. The angle θ described before the breaking is given by

$$\theta = (70° - 2\varphi_1) \quad \ldots \quad (40B)$$

We have already remarked that this motion of the pole over the angle θ may have taken place along the border meridian of Figure 7, but that this need not have been the case. If, however, the path has deviated from this circle, the distance from the initial position can not have attained a value of θ or more at some intermediate moment, because that would have led to the breaking of the crust along another net. We may conclude that, except for this reservation, the determination of the location of the shearing net over the Earth's surface in the position mentioned above allows only the conclusion that the initial position of the pole and the position at the breaking moment must both have been situated on the meridian of 90° east, at least for positive values of φ_1 smaller than 70°, and that their mutual distance θ is given by (40B). If there has been no later movement φ_1 of the pole, the angle θ must have been 70°, and so the initial position of the pole was 20° north in 90° east, that is, near Calcutta. If such a movement had taken place, θ could have been smaller but it must have had a value sufficiently large to lead to the breaking of the crust. In this case the total angle described by the pole was

$$(\theta + \varphi_1) = (70° - \varphi_1) \quad \ldots \quad (41)$$

and so the initial position of the pole must have been $(20° + \varphi_1)$ north in 90° east.

A last problem to be taken up is the question of the forces needed for the rotation of the crust. These forces consist of two parts: First, that which is required for the increase of the stresses dealt with in this Chapter, and second, the part needed for the overcoming of the friction at the lower boundary of the crust. In view of the nearly complete adjustment of the isostatic equilibrium of the crust, there seems to be reason to expect that the second part will be relatively small, but it is difficult to arrive at a reliable estimate of its order of magnitude. We can affirm, however, that if we assume that the forces causing tectonic movements in parts of the crust are brought about by subcrustal currents, those same currents must be able to bring about a gliding of the whole crust over the Earth; from this standpoint it is likely that such movements are possible. Another argument for assuming its possibility may be found in the usually adopted viewpoint that, at a sufficiently great depth, the materials of the Earth react in a purely viscous way, and that, therefore, even the smallest momentum will bring about motion, although the speed will be proportionally small. If this viewpoint is rigorously true, this part of the forces required might even be quite negligible.

The first part can be derived from the formulas of this Chapter. We may determine the deformation energy from the formula

$$A = [(m+1)/2mE](\sigma_x^2 + \sigma_y^2 + \sigma_z^2) + [(m+1)/mE](\tau_x^2 + \tau_y^2 + \tau_z^2) - (1/2mE)(\sigma_x + \sigma_y + \sigma_z)^2$$

which in our case reduces to

$$A = [(m+1)/2mE](\sigma_\delta^2 + \sigma_\alpha^2) + [(m+1)/mE]\tau^2 - (1/2mE)(\sigma_\delta + \sigma_\alpha)^2$$

Introducing (13) and integrating over the whole crust we find

$$A = (32/15)[m/(5m+1)]\pi E \beta^2 T R^2 \sin^2\theta \quad \ldots\ldots\ldots\ldots\ldots \quad (42)$$

Formula (42) agrees with that found by Kuiper for $m = 3$ in his study of shifts of the pole caused by the "Polfluchtkraft" [KUIPER, 1943, p. 86].

Differentiating this formula with regard to θ we find the momentum of forces, M, required to increase the angular distance θ from the initial position of the pole is as in (43).

$$M = (32/15)[m/(5m+1)]\pi E \beta^2 T R^2 \sin 2\theta \quad \ldots\ldots\ldots\ldots\ldots \quad (43)$$

For this deduction we have assumed that the motion of the pole occurs along the great circle connecting its initial and final positions, and that, therefore, M works around the axis perpendicular to the plane of this great circle, that is, around the same axis around which θ is measured. If the axis of the momentum has another position, the rotation of the crust around this axis over an angle $d\epsilon$ will be larger than the increase $d\theta$ of θ, and the formula for M has to be multiplied by $(d\theta/d\epsilon)$; this factor is always smaller than unity.

According to (43) the maximum value of M occurs for $\theta = 45°$. Introducing again $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, $\beta = (1/297)$, $T = 30$ km, and $R = 6371.2$ km we find that this maximum is $M_{max} = 1.76 \times 10^{20}$ kg km, and for $\beta = (1/210)$ this maximum is $M_{max} = 3.53 \times 10^{20}$ kg km. These values do not represent momentums of improbable magnitude. If we should have a subcrustal current in an area near the equator able to bring about a compression in the crust of 100 kg/cm^2 over the whole thickness of the crust of 30 km and over a horizontal extension of 1000 km, this would represent a momentum of

$$M = 6370 \times 30 \times 1000 \times 100 \times 10^{10} = 1.9 \times 10^{20} \text{ kg km}$$

As a stress of 100 kg/cm^2 is no doubt only a small fraction of the stress required to bring about a tectonic deformation, we may expect that the currents needed for such phenomena will be more than powerful enough to give rise to the elastic deformation of the crust accompanying shifts of the crust around the Earth.

The momentum of the "Polfluchtkraft" found by KUIPER [1943] for the present period is $M_P = 3 \times 10^{19}$ kg km and for the maximum value in former periods $M_{P\,max} = 3.5 \times 10^{19}$ kg km. We see that if the values of E adopted in this paper are right, this value is not sufficient to expect the "Polfluchtkraft" to have played a prominent part in possible movements of the crust around the Earth. It is, however, not negligible, and this result, already found by Kuiper, is interesting; although the "Polfluchtkraft" is so small that it cannot by its direct action bring about larger stresses in the crust than a few kg/cm^2, it is able, if the friction at the lower boundary of the crust is negligible, to give rise to fairly great shifts of the poles with accompanying crustal deformation stresses of hundreds of kg/cm^2. For the present flattening the equation $M_{p\,max} = M$ gives, according to (43) a value of θ of about 6°, and this corresponds to a maximum stress $\sigma_{\delta m}$ of about 200 kg/cm^2. It is even clear that in case a greater value of θ already exists because of other causes, the "Polfluchtkraft" may still bring about increases of θ provided the axis of its momentum does not coincide with the axis about which θ is measured, and the corresponding factor $(d\theta/d\epsilon)$ mentioned above is small enough to reduce M below the value of Mp. Lastly we may remark that the "Polfluchtkraft" at a very early date of the history of the Earth's crust may have been larger than the present topography accounts for; in fact we know nothing about the topography in those early periods. So we may conclude that although it is probable that the "Polfluchtkraft" has not been the principal agent in bringing about the rotation of the crust around the Earth, it is possible that it has contributed to it.

Returning to the problems connected with a change of the flattening we have still to investigate the way we may expect the shearing of the crust to occur when the limit the crust can stand is exceeded. We know in this case the planes in which the principal stresses work; they are the normal cross-sections of the crust through the parallels and the meridians. The principal stresses themselves are given by (5C) for σ_δ and (5D) for σ_α. Adopting again Bylaard's and Van Iterson's theory about the direction of the shearing planes, we shall apply (22C) to obtain the angle ψ these planes make with the meridian; we introduce $\rho_1 = \sigma_\alpha$ and $\rho_2 = \sigma_\delta$. We thus find

$$\cos 2\psi = -(2/3)[(\cos^2\delta - 1/3)/\sin^2\delta\,] = (4/9)[(3/2) - \operatorname{cosec}^2\delta\,] \quad \ldots\ldots\ldots (44)$$

For $\delta = 90°$, that is, for the equator, we find $\psi = \pm 38°35'$ and for $\delta = 54°44'$, that is, $\varphi = 35°16'$, we have $\psi = \pm 45°$ and so at this latitude the two shearing planes enclose right angles. For $\delta = 31°05'$, that is, for $\varphi = 58°55'$, the value of ψ is $\pm 90°$ and so here the two directions both coincide with the direction of the parallel. For larger values of φ, (44) no longer gives real solutions, and so according to this Formula no shearing is possible here. The meaning of this result is that in this area no directions can be found for which the length dimension remains unaltered during the deformation, and so Bylaard's hypothesis leads to the conclusion that no shearing can occur.

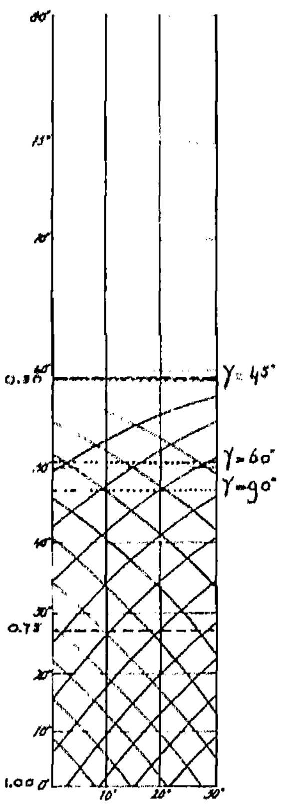


Fig. 9--Shear pattern in Mercator projection for a change of the flattening. The dashed lines indicate shear intensity; the dotted lines the possible angle of the shear planes with the crust

Figure 9 shows the Net in Mercator projection as it follows from (44). It is not in good agreement with the directions of the topography over the Earth's surface. In the North Atlantic, for example, it does not show the asymmetry of the two directions with regard to the north direction. We could improve it by assuming that, since the shearing, a small shift of the crust around the interior has taken place. Net 3 has been derived from Figure 9 by adopting a shift of the North Pole over 10° in the sense of the meridian of 90° west of Greenwich. In this way the asymmetry of the Net in the North Atlantic is brought into harmony with that of the topography. In Chapter III we shall find, however, that this Net is still far from showing the same correlation to the topography over the Earth's surface as that given by the hypothesis of a shift of the poles.

Figure 9 shows two other systems of lines besides the curves of the shearing net; they correspond to the curves in Figure 7. The stippled lines indicate the points where the shear planes have the same inclination with regard to the plane of the crust. To derive this angle we have again adopted the second hypothesis about this point, according to which the inclination, γ, of the planes is such that the energy spent in the boundary zone between the elastic and the plastic deformation is a minimum. We have applied (32), therefore, to find the value of ψ corresponding to a certain value of γ and then (44) to derive the latitude, φ, at which this occurs. We thus obtained for values of $\gamma = 90°$, 60°, and 45°, values of $\varphi = 47°20'$, 50°48', and 58°55', respectively. At all latitudes below 47°20' the angle γ is 90°, that is, the shear planes are normal to the crust.

The second set indicated by broken lines gives the points where the critical stress σ_v has a value of 75 per cent and 50 per cent of the maximum value found for $\varphi = 0$. They may give an idea where shearing

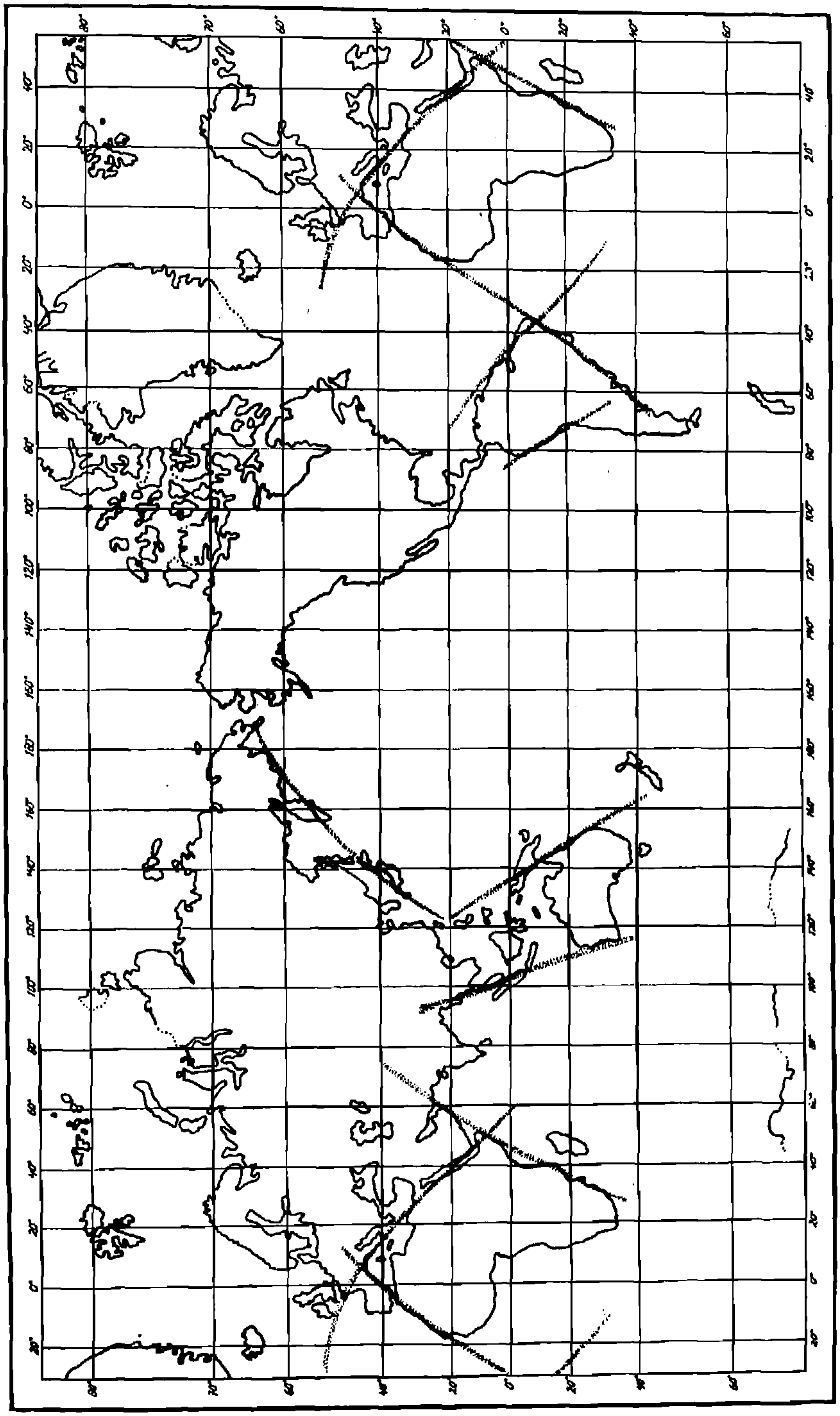


Fig. 10--Supposed major shear zones of the Earth's crust

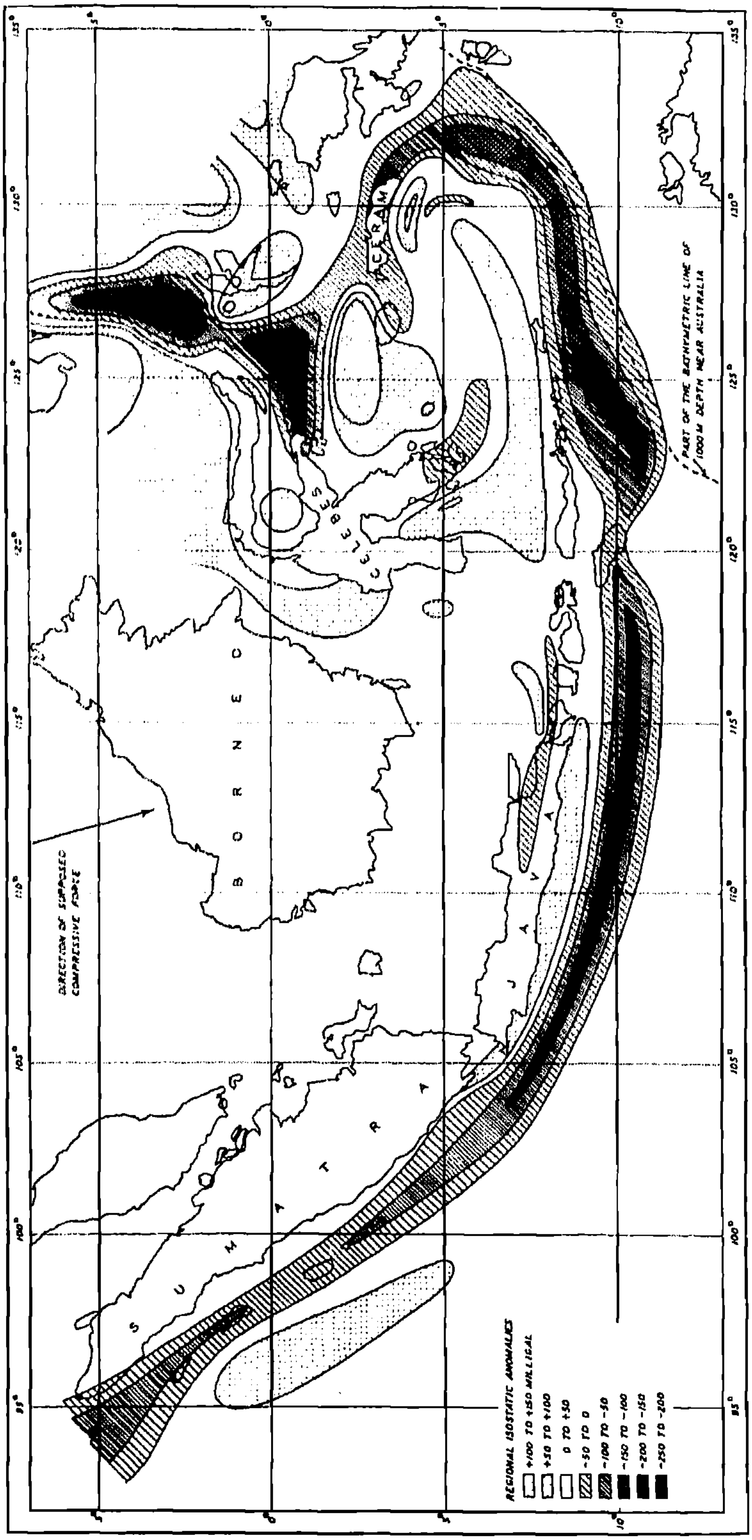


Fig. 11--Gravity anomalies in Dutch East Indies

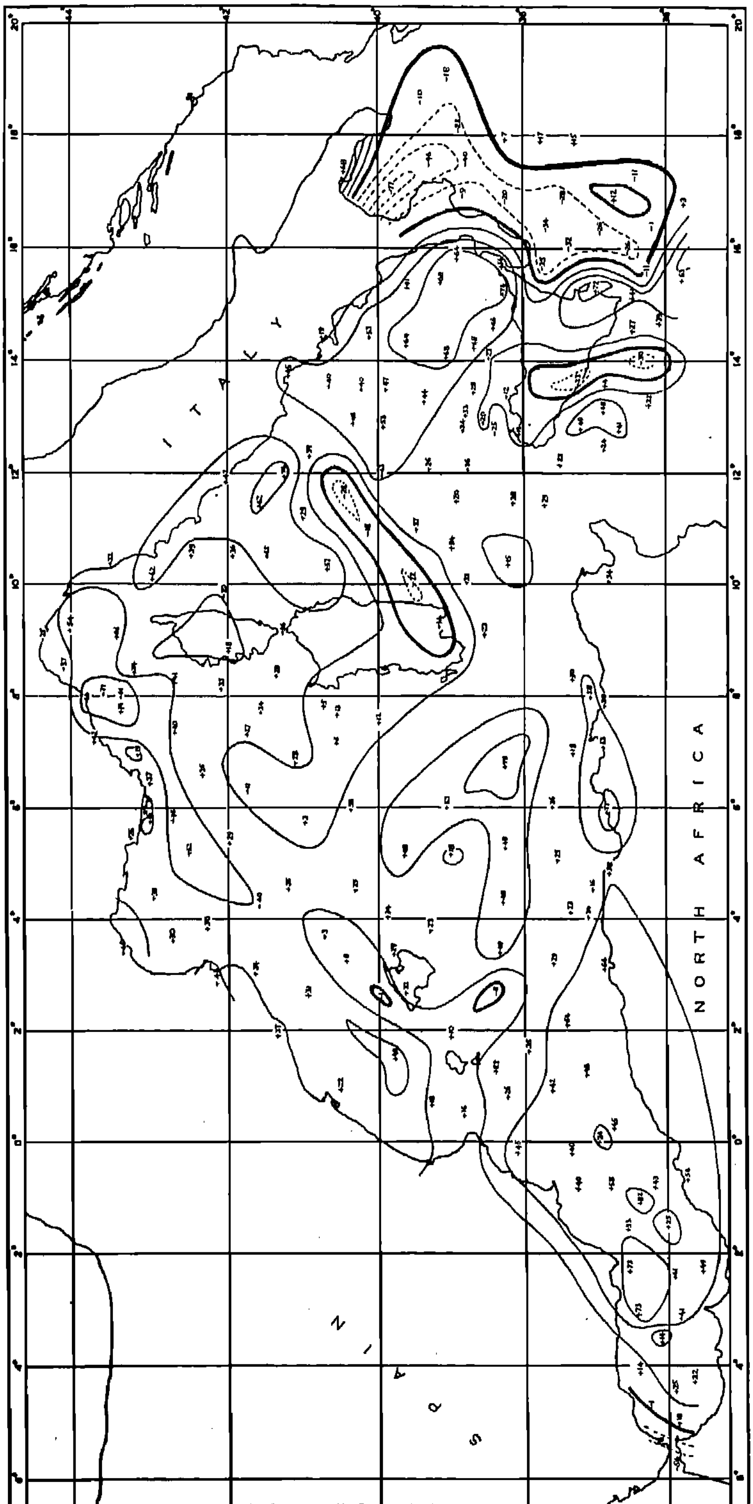


Fig. 12--Gravity anomalies in Mediterranean Area

is most likely to occur. For deriving σ_v we have again used (36B) in which we introduced $\rho_1 = \sigma_\alpha$ and $\rho_2 = \sigma_\delta$ given by (5D) and (5C). We thus obtain

$$\sigma_v^2 = \left\{[m/(5m+1)]\Delta E\right\}^2[7\cos^4\delta - (26/3)\cos^2\delta + (31/9)] \quad \ldots\ldots (45)$$

The first factor is constant, the second variable; the last reaches its maximum value of (31/9) for $\delta = 90°$, that is, for the equator. Dividing by this value, changing over from δ to φ and taking the square root we get

$$\sigma_v/\sigma_{vm} = \sqrt{(63/31)\sin^4\varphi - (78/31)\sin^2\varphi + 1} \quad \ldots\ldots (46)$$

By means of (46) it is easy to deduce that a value of 75 per cent of this ratio occurs for $\varphi = 27°13'$ and of 50 per cent for $\varphi = 45°$ and $58°55'$. Between the two latter latitudes the ratio has a minimum value. As, according to this hypothesis, no shearing takes place at higher latitudes than $58°55'$, we may conclude that shearing may not be expected for latitudes exceeding 45°.

The maximum value of the critical stress may be deduced from

$$\sigma_{vm} = [(m\sqrt{31})/3(5m+1)]\Delta E \quad \ldots\ldots (47)$$

Introducing the values of $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, and $\Delta = [(1/210) - (1/297)] = 0.00140$ we find $\sigma_{vm} = 500$ kg/cm^2. This result confirms our conclusion that the stresses in the case of a change of the flattening of this amount are not quite sufficient to make probable a world-wide breaking catastrophe.

In this Chapter we have dealt with two possibilities for explaining the bilinear pattern of extensive parts of the Earth's surface--a shift of the poles and a change of the flattening. We have not yet investigated the possibility of these phenomena occurring both at the same time. This investigation may be reserved for a future occasion.

CHAPTER III

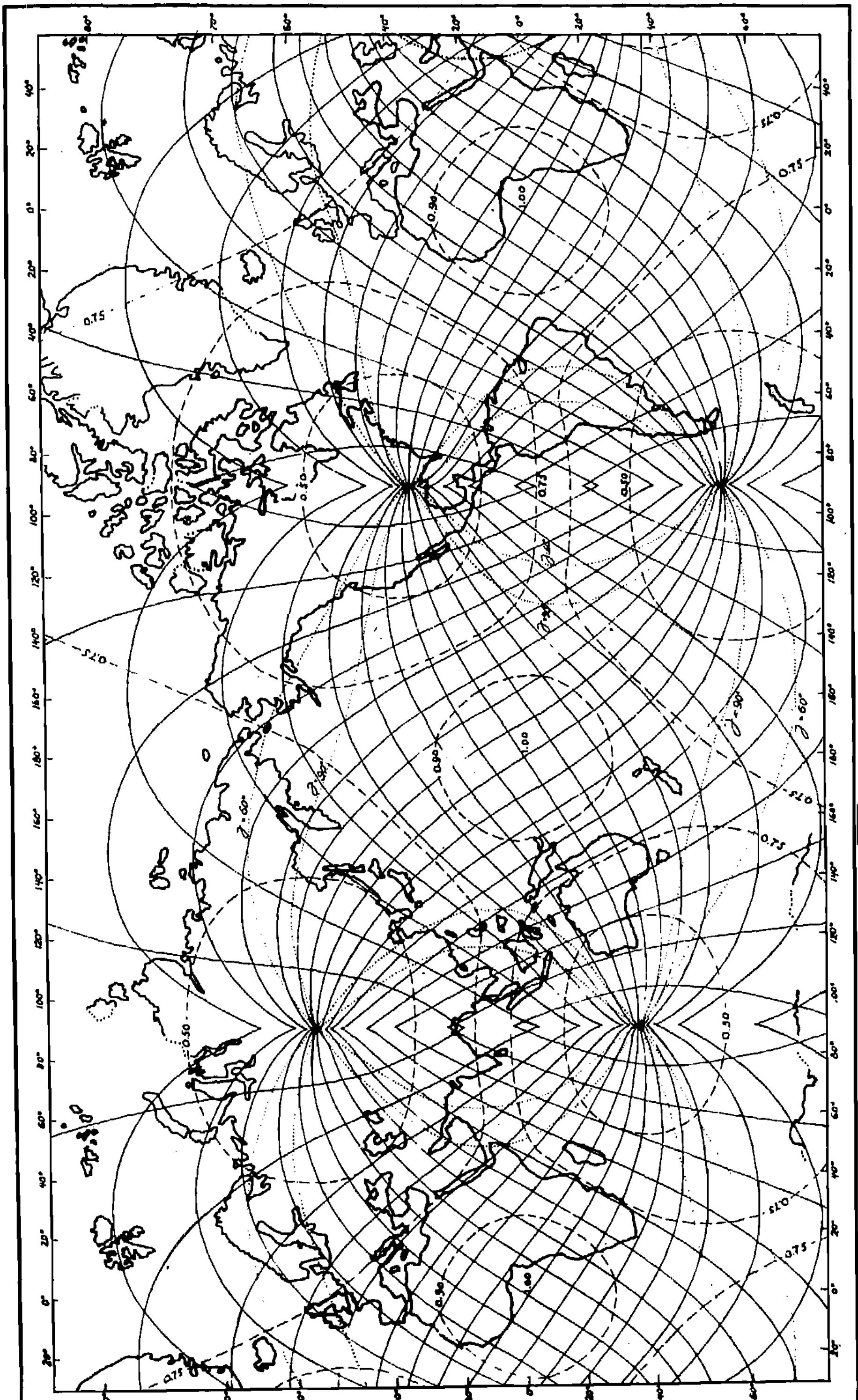
The Evidence at the Earth's Surface of Nets of Fault Planes in the Crust

In this Chapter we shall investigate the evidence at the Earth's surface shedding light on the question whether the crust has been subject to shearing according to one of the two hypotheses of this paper--a shift of the poles or a change of the flattening. We may bring this evidence under three heads, namely; (a) the topography, (b) the geology, and (c) the geophysical, especially the gravimetric and seismic results; the second are more vague and uncertain than the others. We shall briefly examine here these three sources of information.

Taking the topography first, it is clear that practically all phenomena leading to vertical movements of the crust must bring about differential elevations of the crustal blocks on both sides of a fault plane, and so the situation of such a plane must show in the topography. We shall come back to this point in the next Chapter. A second and important way in which the topography is affected is brought about by the volcanism along the fault planes; this also will cause the disclosing of these planes at the surface. Especially in the oceans where no erosion disturbs the topography we may consider the latter as a valuable guide for finding the fault planes of the crust. Geological evidence is practically absent in these parts.

For the continents the problem is more complicated. In the first place erosion so strongly influences the topography that in many cases it must obliterate the effects of fault planes or at least render them more difficult to read, although in the detailed topography it may help to divulge them because of the infiltration of water in the clefts and frost effects. In the second place the topographic evidence is supplemented here by the geological data, which in many cases will give a more direct and more positive indication of the presence of shear planes than any other evidence can provide. So, for most continental areas, no final conclusions can be drawn without a thorough geological study of the data.

Considering these circumstances, the writer, not being a geologist, has refrained from attacking the problem for the continents; he restricted himself to a statistical investigation of the submarine topography. As this is fairly well known over about one-half of the Earth's surface, this source of information gives a good approach to the problem. We shall find that it shows a remarkably strong correlation to Net 1 and so indicates a polar shift along the meridian of 90° east as mentioned above. The other two Nets show less correlation.



Net 1--Shear pattern in Mercator projection for a shift of the poles over 70° along the meridian of 90° longitude. The dashed lines show shear intensity; the dotted lines the possible angle of the shear planes with the crust

As for the evidence on the continents we need not altogether leave it out of our considerations; a great mass of data regarding the presence of fault planes--not known to the writer when he undertook this investigation--already has been brought together by geologists such as Hobbs, Sederholm, Daubrée, and Sonder, who in their lineament tectonical publications have already given many indications in favor of a world-wide shearing net of the Earth's crust. In the second part of this Chapter we shall discuss how far these results are in agreement with Net 1, and we shall find agreement for nearly all the instances. As this material has been discovered independently of any theory and as thus a biased judgment is out of the question, we may consider it as a striking support of our polar shift hypothesis. The same may be said of Krenkel's results for the African Continent, which have likewise been dealt with and which also fit remarkably well in Net 1.

Turning to the geophysical evidence, the gravity field in some cases may likewise give valuable data for our problem. In the first place it discloses the trend of subterranean structures which, evidently, may be correlated with crustal shear planes. In the second place, for areas where great buckling of the crust has occurred, as, for example, the East Indian Archipelago, it can provide evidence about the direction in which the crustal compression has operated; this direction may also be connected with the fracturing of the crust and in the East Indies it indeed coincides with one of the two directions of our Net. We shall come back to these and other points.

The seismic results may give indications in two ways. In areas where records of a sufficiently numerous set of seismological stations are available we may obtain the position in space of the fault planes along which movements take place. Such results are thus restricted to areas in land or in archipelagoes and we can not expect through seismic data to find large parts of the shearing net of the Earth's crust. Obviously we thus can only find planes along which movements are still active in the present period.

In the second place it may be possible in certain areas, where geological evidence for shearing is also available, to combine the epicenters of earthquakes in lines along which we may suppose the shearing movement of the crust to proceed. In the second part of this Chapter we shall examine the maps made in this way by Sieberg for many areas; for the greater part their lines are in good harmony with our Net. So by means of such maps, although more or less conjectural in themselves, we may get valuable confirmation about the location of the fault planes of the crust where movements are still going on.

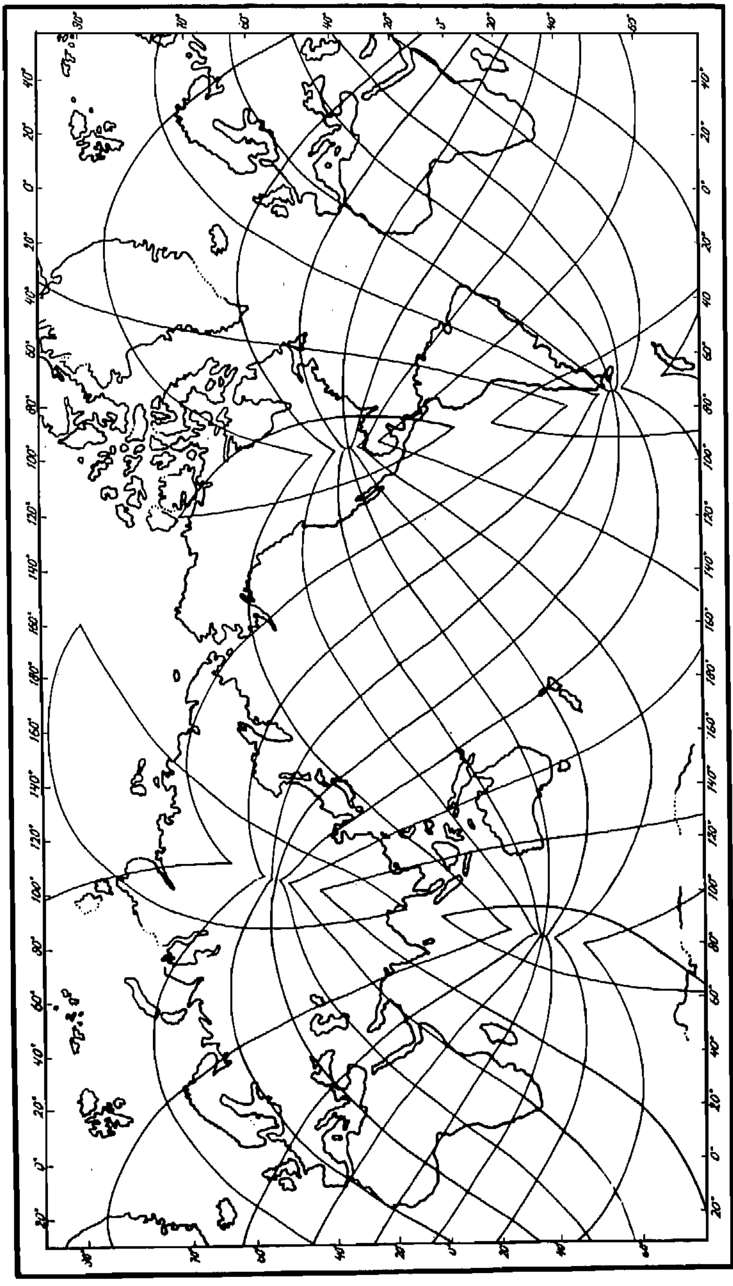
In studying the correlation of the submarine topography with Net 1 we have to bear in mind that this Net is based on a few simplifying assumptions, that is, the uniform thickness, the homogeneity, and the isotropism of the Earth's crust, which are certainly not absolutely true. We have to expect, therefore, that the shear planes of the crust will not accurately follow the mathematical net which has been deduced; it is probable that they will show smaller or larger deviations. For taking this into account in the following investigation we shall neglect angles up to 12° between topographic features and directions of the Net, or, in other words, if the deviation is smaller than that limit we shall consider them as still in harmony.

One of the best ways to study the correlation, no doubt, would be to construct in each area a rose for which the radii in the different directions would be proportional to the frequency of this direction in the topographic features; these roses would allow a good estimate of the degree of correlation with Net 1. In general, however, the submarine topography is not sufficiently known in detail to give a basis for such a procedure in a limited area; as it is we should have to extend the area so far that the directions of the Net would vary too much from one end to the other.

We shall have, therefore, to follow another line of research. After careful consideration of the problem the writer arrived at the following solution. For each area determine the sum of the lengths of the topographic lines in harmony with the Net and also for the lines agreeing with the two sets of directions bisecting the angles of the Net; in both cases neglect deviations up to 12°. By taking the ratio of the first sum divided by the second we obtain a value for comparing the correlations with the topography for both sets of directions. If this ratio is systematically larger than the unity, we may affirm that Net 1 has at least a correlation equalling this ratio. If the bisecting net has itself a correlation with the topography, the correlation of Net 1 is correspondingly greater. This case is not to be excluded, because in extensive areas the directions of the bisecting net coincide more or less with the north-south and east-west directions, and many geologists think that at least the first of these two directions occurs more frequently than normal. So by adopting our ratio as a figure for the correlation of Net 1 with the topography, we shall certainly not over-estimate our result.

We shall also submit Nets 2 and 3 to this procedure; for each of them we shall determine the sum of the lengths of the topographic lines in harmony with the net, and we divide the result by the same quantity as used for the comparison of Net 1, that is, by the sum of the topographic lines in agreement with the bisecting directions of Net 1. These last determinations need not be made with the same care as for Net 1; it is sufficient to obtain a precision allowing the conclusion that the correlation with the topography of these Nets is smaller than that of Net 1.

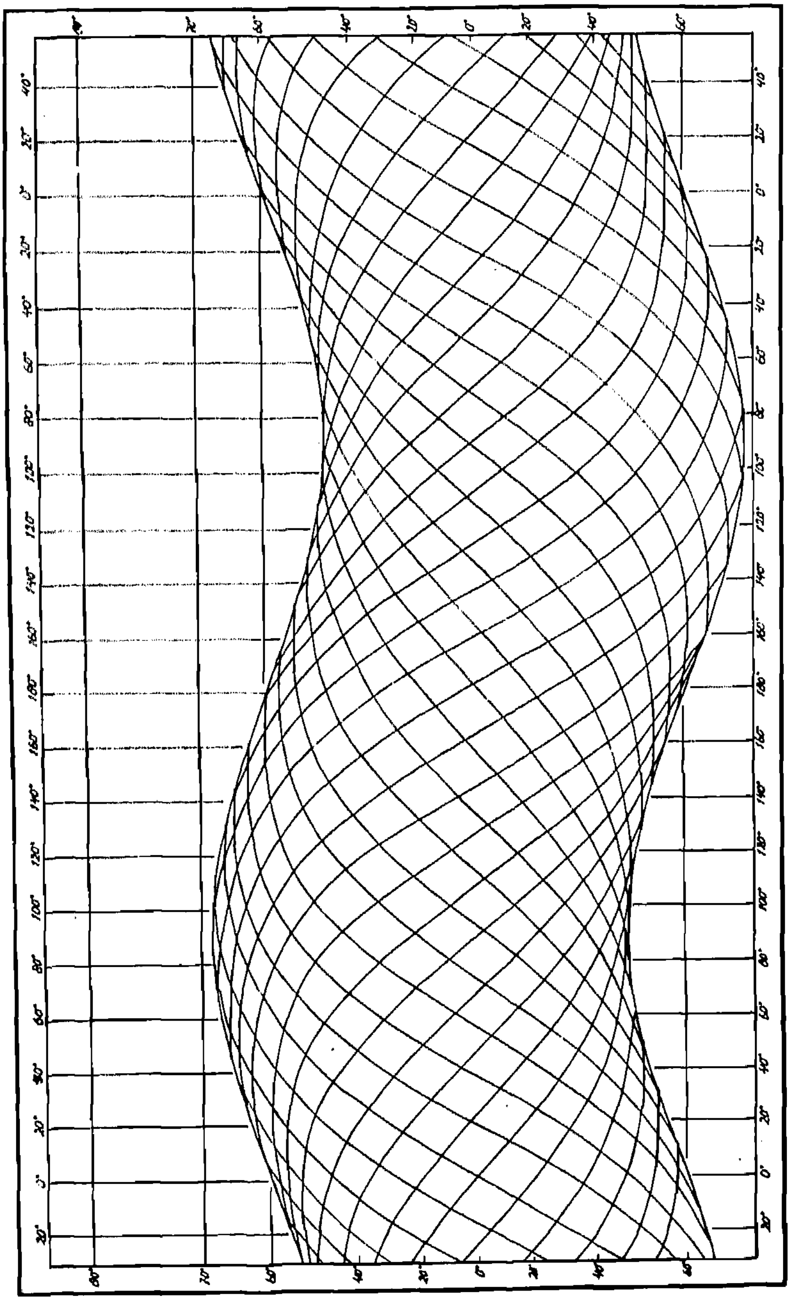
For these determinations we shall use only charts with contour lines at intervals of a thousand meters or less. As the tracing of these lines is often more or less uncertain, we shall give a weight of one-half to a topographic feature indicated by only one of these lines. For ridges we shall count the two slopes separately; a ridge bordered on both sides by parallel slopes will receive, therefore, a double weight, unless on each side it is only indicated by one contour line; in



Net 2--Shear pattern of Net 1 in Mercator projection after additional polar shift over an angle $\varphi_2 = 10°$ in longitude 0°

this last case the weight is equal to unity. We shall not count each contour line separately with the same weight, as we might perhaps be tempted to do, because we thus would give undue weight to the slopes extending over great differences in depth. As we have already mentioned, we shall assign a weight of one to each slope indicated by at least two contour lines. We shall not take account of slopes of less than 500-meter difference of depth, and so in shallow seas and over coastal shelves, where we usually have contour lines at short depth intervals, we shall in general not include any lines.

For our investigation we shall successively survey the following areas: the North Atlantic, the South Atlantic, the Mediterranean combined with the Red Sea, the Black Sea, and the Caspian



Net 3--Shear pattern of Fig. 9 for change of flattening in Mercator projection after additional polar shift of 10° along the meridian of 90° longitude

Sea, the Indian Ocean, the North Pacific, and the South Pacific. In the Arctic Sea the number of soundings is insufficient for our purpose and the same is true for the seas surrounding the Antarc tic Continent--for these seas we can only remark that the general trend of the deep basins does not contradict the directions of Net 1.

For the North Atlantic a fairly detailed depth survey has been made to high latitudes and so we can extend our investigation from the Equator up to latitude 70°north. The writer employs a new chart of the North Atlantic to be published shortly in a report on the gravity observations at sea, it extends from 0° up to 50° north latitude. It has been drawn by J. W. Bloem of the Hydrographic Office of the Netherlands Navy, who compiled it from the third edition of the "Carte Bathymétrique des Oceans" [to be henceforth indicated by "Monaco chart" supplemented by the number of the edition] corrected to 1940 from various sources, that is, mainly from United States Hydrographic Charts Nos. 5486 and 5487 and from soundings by the Altair in 1938 [DEFANT, 1939; WÜST, 1939]. North of 50° we can use the Monaco chart (3rd ed.) and the "Tiefenkarte der Dänemark Strasse, Irminger See, u. s. w." of G. Bönecke [1936].

For the South Atlantic the writer has used the chart of the Meteor Expedition [BORN, date not noted], which extends farther south than the third edition of the Monaco chart. He investigated the area from 0° to 60° south latitude and from 65° west to 25° east.

The Mediterranean, the Red Sea, the Black Sea, and the Caspian Sea have been studied by means of the Monaco chart.

For the northwestern part of the Indian Ocean the writer used the chart of the "John Murray Expedition" [WISEMAN, date not known] and for the remainder, the Monaco charts. These last parts are only poorly surveyed, especially at higher latitudes, and so the writer restricted the investigation to the part north of 45° south latitude further limited by the meridians of 25° east and 145° east. West of the meridian of 90° east, he used the third edition of the Monaco chart but east of it the second edition. In the last part he could supplement this evidence by the soundings of the submarine Hr. Ms. K XVIII of the Netherlands Navy taken during its expedition of 1934-35; it gave rise to some changes in the tracing of the contour lines.

For the study of the North Pacific the writer could use the provisional edition of the chart of the United States Hydrographic Office of 1939, which was kindly given to him during his stay in Washington for the Seventh General Assembly of the International Union of Geodesy and Geophysics in 1939. It is a remarkable improvement on previous charts, which was rendered possible by more than 180,000 new echo soundings made by vessels of the United States Navy in recent years. It thus gives a fairly detailed representation of the submarine topography over a great part of this ocean. The chart extends to 5° south latitude, and the writer, therefore, extended his survey of the North Pacific to this same latitude.

For the South Pacific no other charts were available than the second edition of the Monaco charts and, as in the eastern and southern parts of this ocean the depth figures are scarce and the tracing of the contour lines uncertain, the writer did not extend the investigation further than to 135° west longitude and to 45° south latitude for the part west of longitude 175° west and to latitude 30° south for the part between longitudes 135° west and 175° west. For the western limit the meridian of 145° east was taken.

With only one exception the charts used are drawn on Mercator projection, and so the directions are not distorted. Only the "Tiefenkarte der Dänemarkstrasse, u. s. w." is represented in another, not conformal, projection; this has been taken into account as well as possible. For measuring the lengths on the charts, the areas have been divided in horizontal strips of 10° or 15° breadth, and for each strip the lengths have been totalled and the sum multiplied by a common reduction factor corresponding to the mean value for this strip. The figures for the Red Sea, although combined with those of the Mediterranean, have been reduced separately. Table 2 summarizes the results for all these determinations. The columns successively give the sum L_1 of the lengths in correlation with Net 1, L_2 for Net 2, L_3 for Net 3, and L_4 for the bisecting net of Net 1. The last three columns contain the ratios (L_1/L_4), (L_2/L_4), and (L_3/L_4). The last line of each subdivision of Table 2 gives the sums of L_1, L_2, L_3, and L_4 and the ratios of these sums; it thus provides us with the result for the whole ocean. Table 3 puts together the results for the different oceans; in a first column the measured areas have been added.

Table 2--Summary of lengths on charts for latitude intervals

Latitude interval	L_1	L_2	L_3	L_4	(L_1/L_4)	(L_2/L_4)	(L_3/L_4)
° °	km	km	km	km			
North Atlantic Ocean, from 0° to 70° north latitude							
70 N - 60 N	7100	7100	0	2300	3.08	3.08	0.00
60 N - 50 N	5300	5300	1800	2900	1.83	1.83	0.62
50 N - 40 N	11200	11200	5700	4000	2.80	2.80	1.42
40 N - 30 N	17400	17400	10900	5000	3.48	3.48	2.18
30 N - 20 N	13500	13500	12000	4400	3.07	3.07	2.73
20 N - 10 N	6200	6200	5500	2300	2.69	2.69	2.39
10 N - 0	10900	10900	5000	2200	4.95	4.95	2.27
Totals	71600	71600	40900	23100	3.10	3.10	1.77
South Atlantic Ocean, from 0° to 60° south latitude and 65° west to 25° east longitude							
0 - 15 S	10100	10100	9000	5800	1.74	1.74	1.55
15 S - 30 S	10700	10700	10700	6100	1.75	1.75	1.75
30 S - 45 S	10600	10600	10600	4300	2.46	2.46	2.46
45 S - 60 S	7800	7800	6300	3400	2.29	2.29	1.85
Totals	39200	39200	36600	19600	2.00	2.00	1.87
Mediterranean, Red Sea, Black Sea, and Caspian Sea							
-- --	15500	15500	8800	7200	2.15	2.15	1.22
Indian Ocean to 45° south latitude and 25° east to 145° east longitude							
25 N - 0	29000	13100	19300	9600	3.02	1.36	2.01
0 - 15 S	14300	10900	14300	7500	1.91	1.45	1.91
15 S - 30 S	13700	9400	7500	3300	4.15	2.85	2.27
30 S - 45 S	11100	10700	3500	3000	3.70	3.57	1.17
Totals	68100	44100	44600	23400	2.91	1.88	1.90
North Pacific Ocean from 60° north to 5° south latitude							
60 N - 45 N	10700	10700	1600	3100	3.45	3.45	0.52
45 N - 30 N	18400	18400	12500	8200	2.25	2.25	1.53
30 N - 15 N	32100	32100	18200	13200	2.43	2.43	1.38
15 N - 5 S	29500	27500	29500	16400	1.80	1.68	1.80
Totals	90700	88700	61800	40900	2.22	2.17	1.51
South Pacific Ocean from 5° south to 45° south latitude and 145° east to 175° west longitude and from 5° south to 30° south latitude and 175° west to 135° west longitude							
5 S - 15 S	18300	18300	18300	8500	2.15	2.15	2.15
15 S - 30 S	15400	15400	10100	12400	1.24	1.24	0.81
30 S - 45 S	6900	6900	6900	3900	1.77	1.77	1.77
Totals	40600	40600	35300	24800	1.64	1.64	1.42

Table 3--Summary of Table 2 for oceans and areas

Ocean or group	Area	L_1	L_2	L_3	L_4	(L_1/L_4)	(L_2/L_4)	(L_3/L_4)
	$10^6 km^2$	km	km	km	km			
North Atlantic	35.2	71600	71600	40900	23100	3.10	3.10	1.77
South Atlantic	40.5	39200	39200	36600	19600	2.00	2.00	1.87
Mediterranean, Red Sea, Black Sea, Caspian Sea .	8.5	15500	15500	8800	7200	2.15	2.15	1.22
Indian Ocean	49.8	68100	44100	44600	23400	2.91	1.88	1.90
North Pacific to 5° south. .	86.8	90700	88700	61800	40900	2.22	2.17	1.51
South Pacific south of 5° south	28.8	40600	40600	35300	24800	1.64	1.64	1.42
Totals	249.6	325700	299700	228000	139000	2.34	2.16	1.64

The last line of Table 3 contains the sums of the areas and of the lengths L_1, L_2, L_3, and L_4 in the (L_1/L_4), (L_2/L_4), and (L_3/L_4) ratios; these ratios are not the mean values of the corresponding columns.

We see that the total of the areas surveyed is $250 \times 10^6 km^2$; as the whole surface of the Earth is $510.1 \times 10^6 km^2$, our determinations have covered practically one-half of it. This is sufficient, no doubt, for attributing great weight to our evidence. We shall, in the first place, use this evidence for the comparison of the three Nets. For the third Net, which corresponds to a change of the flattening, our conclusion can be simple; it is clear that its correlation with the topography is less than for Net 1. This is especially clear for those parts of the oceans where the nets differ most, that is, for high latitudes. For the belts of 70° to 60° and 60° to 50° of the North Atlantic we find ratios for Net 3 of 0.00 and 0.62, while Net 1 shows 3.08 and 1.83. The ratio 0.00 for Net 3 indicates that this Net does not show lines at all between 60° and 70°, while Net 1 in this area shows a correlation of 3.08; this is evidently strongly in favor of Net 1. For the belt of 30° to 45° of the Indian Ocean we find 1.17 for Net 3 against 3.70 for Net 1; for the belt of 60° to 45° of the North Pacific the values are 0.52 against 3.45. Only the value 1.85 for the belt of 45° to 60° of the South Atlantic shows less difference with the ratio 2.29 of Net 1. For the South Pacific the area that was investigated does not reach the latitude where the Nets differ much. Considering these results we may safely conclude that the hypothesis of a change of the flattening does not fit the evidence as well as that of a shift of the poles. We shall not investigate the former any further in this or the next Chapter.

The question whether Net 1 or Net 2 shows the greater correlation with the topography has less importance for the study of the history of the Earth; both Nets are based on the same hypothesis of a shift of the poles and the only point is whether, since the shearing catastrophe, the pole has slightly wandered in a sense at right angles to the plane of symmetry of the shearing net. The evidence does not give much support for this last supposition. Although the ratios for Net 2 differ less from those of Net 1 than those of Net 3, one of the two areas where the Nets deviate most from each other shows evidence in favor of Net 1. These areas are situated near and over the meridians of 90° east and 90° west and the Indian Ocean provides a ratio of 1.88 for Net 2 against 2.91 for Net 1. The second oceanic part that could have given information is the southeastern Pacific, but in this area not enough is known of the topography to allow a determination of the correlation. For the Northern Hemisphere the meridians of 90° east and 90° west are located on the continents. We may conclude that the evidence, as far as it goes, is in favor of Net 1, but that this conclusion is less decisive than for the comparison to Net 3. We shall henceforth keep to Net 1 in our subsequent discussions.

Examining Tables 2 and 3 we see that for all the areas the ratio for Net 1 is greater than unity; in Table 3 it varies from 1.64 to 3.10. This is obviously a strong indication that the correlation to the topography is not fortuitous. This conclusion is further supported by the fact that the two highest values of 3.10 and 2.91 have been found for those oceans where the topography is best known, namely, the North Atlantic and the Indian Ocean. For the latter much of the information is based on soundings of the "John Murray Expedition" in the northwestern part. For the Mediterranean the topography is likewise known in detail, but the ratio is somewhat less. We may perhaps explain this by the fact that this area belongs to a zone of tectonic folding, and that this part of the topography does not depend directly on the shearing net. It is likely that this same explanation may be given for the relatively small value of the ratio for the southwestern Pacific.

We might ask whether it is possible to obtain an impression of the probability that no real cause would be behind our correlation, or, in other words, that these values of the ratio only accidentally deviate from unity. If no special directions dominate in the submarine topography, we may expect the value of this ratio to tend to this last value, and we might suppose that deviations from it would follow Gauss's law of probabilities. On this basis we may make an estimate as follows. According to Gauss's law the probability of a deviation between x and (x + dx) is given by $ydx = (1/m\sqrt{2\pi})e^{-x^2/2m^2}dx$, in which m is the mean value of the deviations. This last quantity is unknown in our case. We shall meet this difficulty by deriving the maximum value this probability can assume if m varies. By differentiating the formula with regard to m and equating the differential quotient to zero we find m = x, and as the second differential quotient is negative for this value, it is a maximum. Introducing this value of m in the above formula we obtain

$$y_m dx = (1/\sqrt{2\pi e})(dx/x) = 0.24(dx/x) \quad \ldots\ldots\ldots (48)$$

To apply this formula to our problem we introduce for x the deviation of the mean value of (L_1/L_4) from unity for a special area, for example, the North Atlantic, and for dx the range between the extreme values of this quantity. This last substitution is, of course, a rough procedure, but as we require only an approximate estimate of the probability, we may permit it. According to our choice of m we find a maximum value for this probability.

Applying our formula to the North Atlantic we thus obtain for the probability that a value of (L_1/L_4) is inside the total range $y_m dx = (0.24)(3.12/2.10) = 0.36$, and for the probability that the seven values are all inside this interval we find $0.36^7 = 0.00078$. If we restrict our deductions to the Atlantic between 10° north and 70° north, we have a range of the ratios of 1.65 and we obtain $y_m dx$ - (0.24)(1.65/2.10) = 0.19, and for six values inside this range $0.19^6 = 0.000047$. We see that these probabilities are quite negligible, and so we may conclude that the presence of a dominating system of directions coinciding inside limits of 12° to both sides with our Net is practically a certainty if at least the writer has not, unconsciously, been too much biased in making the measurements. For the other areas we get the same result; for the South Pacific the probability is largest, but even here we find only 0.041, and so we may still neglect it. We come, therefore, to the conclusion that over all the oceans investigated, that is, over half of the Earth's surface, the topography shows a predominance of the directions corresponding to a shift of the poles as assumed.

The great number of topographic features in correlation with our Net produces in itself a problem. We may ask whether it is likely that the Earth's crust under the stresses caused by a shift of the poles will give way in so many places. It is difficult to give a positive answer to this question, because the physical properties of the Earth's crust as a whole are so imperfectly known, but we may probably find a satisfactory explanation by comparing our case to the behavior of steel under stresses exceeding the yield value. If a flat strip of steel is subjected to a slowly increasing tension, plastic deformation sets in at a certain moment and this may be made visible, for example, by polishing the surface; the deformed section then discloses itself by the dimming of the surface. The experiments show that after such a line has formed, the plastic deformation stops at this place and a second one forms, obviously because the deformation has led to a "hardening" of the matter at the former place. In this way a great number of such lines may form in quick sequence to each other. In case the tension is further increased, breaking will occur at one of the sections, but it can not be predicted where this will be. A similar phenomenon might be imagined to occur in the Earth's crust, which, because of the great pressure in its major part, may be expected to behave as a plastic material.

Another point difficult to decide by theoretical deduction is the question how far and how the deformation will proceed in the areas of smaller stress around the points of zero stress where the curves of the Net converge. It is clear that if the crust has yielded to plastic deformation over great distances the stresses near these points may have increased and may have led to deformations in these areas too, but the distribution of stress may have been changed, and so in this case we may expect other lines of shear. Concluding, we can not suppose Net 1 to be valid for these areas. As, however, we find several topographic features correlated to this Net inside the curves where the critical stress has reached half its maximum value, these areas of non-correlation seem to be restricted to a still more limited extent. We may mention the following examples: The west coast of Australia; the coast of California; and the edge of the shelf northwest of the Bahamas.

One of the most difficult problems connected with the hypothesis of a shift of the poles is the explanation of the correlation of the shearing net and the continental coasts, which the map seems to indicate. It is especially desirable, therefore, to make sure how far this correlation is present. We shall begin here by a statistical investigation along the same lines as made above, but as the lengths of the coast line of each continent are rather small for this purpose, we can not attach too much importance to the figure obtained for the separate continents; for all the continents taken together the results carry more weight.

For our purpose we require the course of the structural boundaries of the continents, that is, of the edges of the continental shelves. As this course is uncertain for the coasts surrounding the Arctic Sea and likewise those of the Antarctic Continent, we shall not include them in our investigation.

In measuring the coast lines in harmony with the directions bisecting the angles of our Net, the writer got the impression that they occurred with greater than normal frequency, and that this figure thus did not provide us with a good basis for comparison. He repeated, therefore, the procedure for the Net given by the meridians and the parallels and found that this sum was indeed smaller than the former for all the continents. Table 4 gives the ratios of the sum L_1' of the coast lines in harmony with Net 1 to the sums L_2' and L_3' for both comparison nets; L_2' refers to the north-south and east-west directions, L_3' to the bisecting directions of Net 1. Nets 2 and 3 have not been investigated.

Table 4--Correlation of the continental coast lines to Net 1

Continent	L_1'	L_2'	L_3'	(L_1'/L_2')	(L_1'/L_3')
	km	km	km		
Eurasia	15780	9010	9050	1.75	1.74
North America	12330	5940	7390	2.08	1.67
South America	11180	7320	7430	1.53	1.51
Africa	8380	6260	7140	1.34	1.17
Australia	8070	4880	7340	1.65	1.10
Totals	55740	33410	38350	1.67	1.45

The coast lines of Eurasia and North America have been measured up to 60° north latitude, and those of Central America have been added to North America. The coasts of the Mediterranean, the Black Sea, the Caspian Sea, and the Red Sea have been omitted, because we can not consider them as having the character of the edge of a continent. For the same reason, all island ridges have been left out. For eastern and southeastern Asia, as elsewhere also, the edge of the shelf has been followed, and so the continental block carrying Sumatra, Java, and Borneo has been included. In the same way New Guinea and Tasmania have been added to Australia. The coasts of New Zealand have not been measured.

Examining the results we see that the correlation is decidedly less than shown by the previous tables for the submarine relief, in which, it may be remarked here, the continental edges have been included. As the differences of L_2' and L_3' for the two Nets of comparison are small, we can not definitely affirm that the bisecting Net has a correlation with the coast lines, although it is possible that this is true. As this remains uncertain, it does not appear justified to prefer the value of 1.67 to that of 1.45 for the ratio of L_1' to the sum of the lengths in harmony with an arbitrary net, and so we shall take the mean of these values, that is, 1.56. Comparing this to the value of 2.34 found above for the submarine topography we see that the deviation from unity is less than half of this last value. Still, it does not seem doubtful that for the continental coasts a correlation exists also, and this is confirmed by applying Formula (48). Taking the mean of the values of the last two columns of Table 4 for each continent, the largest of these figures is 1.88 and the smallest 1.26, and so we may introduce for dx the difference 0.62. We thus obtain, in case we should assume no correlation at all, that the maximum probability of a value of the ratio occurring between these two limits is $(0.24)(0.62/0.56) = 0.265$, and of five values inside this same range $0.265^5 = 0.0013$.

This result does not leave much doubt that a correlation really exists. We may remark, however, that our statistical investigation can only be considered as a first superficial attack of the problem; for a more thorough study we shall have to take into account what we know about the origin of these coast lines. For many of these this is not much, but for all those where we find folded mountain ranges parallel to the coast or where such formations have been present in former periods, we may at least suspect their general trend to have been determined by these phenomena. If we examine the evidence in this regard, we find that only part of these coast lines is in harmony with the Net. For this study the following coasts are to be considered: The west coast of North, Central, and South America; part of the east coast of North America; great parts of the east coast of Asia; the major part of the block limited by Sumatra, Java, and Borneo; part of the coast of

Burma and the Malay States; the south coast of Baluchistan; the northeast coast of Queensland; the west coast of Tasmania and Victoria; the coast of Natal and a small part of the west coast of South Africa near Cape Town. Perhaps we ought to add the edge of the European Shelf from Bayonne to west of Lands End and also northwest Ireland and Scotland, but, as this is questionable, it has not been included. If we measure the lengths of the coast lines here enumerated as far as they are in harmony with the Net and also as far as they agree with the bisecting directions, we find the sum of the first lengths to be $L_1'' = 22930$ km and of the second $L_2'' = 14680$ km. The ratio is 1.56. This is of the same order as the result found above for all the coasts. We have to realize, however, that the lengths are not sufficient to give much weight to this statistical figure. Still the result is such that a correlation of these "folding" coasts with the Net seems likely.

The supposition that for these coasts we may reduce the problem of the correlation with the Net to the question of how the correlation of the trends of crustal folding can be explained, is in harmony with the unmistakable correlation shown by the mountain formations for the continents. For Central Europe, we find the following examples: Hohe Venn and Sauerland; Eifel and Westerwald; Hunsrück and Taunus; Thüringer Wald; Erzgebirge; Sudeten; Böhmer Wald; Schwäbische Jura; Swiss Jura; and a great part of the Alps and the Carpathians. The number of ranges not in harmony with the Net is much smaller. We shall not further discuss this question, however, because here a deeper geological study is required, which the writer does not feel competent to undertake. We may state, nevertheless, that the general trends of the Caledonian and Variscian, as well as the Cenozoic folding in the whole of Europe, clearly seems to show a correlation with the two directions of the Net. This correlation of folding and shearing net is not surprising; as we shall further discuss in the next Chapter, we may expect the presence of shear planes through the crust to affect the trend of folding, and this circumstance may go far in explaining the curious twisted course of the folding axis in many parts of the great geosynclines.

Returning to the problem concerning the continental coast lines, we may conclude that, as far as these lines are determined by crustal folding, the problem may be reduced to the one mentioned above which seems easier to attack. The question may be put whether perhaps in this way a solution may also be obtained for the other coast lines, namely, by the hypothesis that these coasts have been determined in a similar way by earlier folding in old Pre-Cambrian periods. In the next Chapter we shall discuss this possibility and its consequences for the great problem of the origin of the continents. We shall likewise examine another possible explanation for the correlation of coast lines and shearing net.

Before leaving the subject of the evidence provided by the Earth's topography, we have to mention still another group of facts. Examining the map we may be struck by some cases where major topographic features coincide over great lengths with the same, or nearly the same, curve of the Net. It looks as if these curves represent the place where the Earth's crust has finally given way to the stresses after the stage of yielding and "hardening" had been past. If larger movements occur along the shear planes, we may expect them to continue over great distances, eventually from one area of slight deformation to another of these areas. Obviously it is not necessary that this occur over its entire length in exactly the same shear curve; it is clear that it may shift to a neighboring curve and so we must rather expect zones of deformation extending over large distances.

The following instances may be given; they have been marked on the map of Figure 10:

(1) The zone following the east coast of South America, the Sierra Leone Ridge, the northwest coast of Africa, the east coast of Spain, part of the Alps, the Schwäbische Jura, and the Bohemian mountains

(2) The zone following the Carlsberg Ridge, the Red Sea, the west coast of Italy, the south coast of France, the Pyrenees, the European shelf from Bayonne to west of Lands End, and the continuation towards the Mid-Atlantic Ridge

(3) The zone bordering the east coast of Asia

(4) The zone following the east coasts of Africa and Arabia, possibly continuing in the mountains of Baluchistan and Afghanistan towards the Hindu Kush; it may be that we can pursue this zone on the other side via the Cape Ridge, the Meteor Bank, and Bouvet Island towards the South Orkneys and Graham Land

(5) The zone probably beginning in the Chwanben, following the mountains of Burma, the Andaman and Nicobar Islands, Sumatra, and continuing in the west coast of Australia

(6) Possibly a zone from Formosa along the east coast of the Philippines, the west and east coasts of the western part of New Guinea, the northeast coast of Queensland, and the New Zealand Ridge towards New Zealand; it may be that the two last zones more or less find a continuation in the west coast of Victoria and Tasmania and in submarine formations towards Balleny Island and the Ross Sea

(7) A zone following the northeast coasts of the Bahamas and of South America, which may perhaps continue in the Rio Grande Ridge via Tristan da Cunha towards the Atlantic-Indian Ridge

(8) A zone following a great part of the west coast of North America and a part of the west coast of South America, which may perhaps be pursued in this Continent.

Although perhaps part of this material is illusive or caused by accidental coincidence, it does not seem likely that this is the case for all of it. As far as it is real it is a good illustration of the fact that the shearing of the crust does not in itself bring about the topography, but that other causes are responsible. Otherwise we should not find so many entirely different features in the same curve as is, for example, the case for the first two curves of the above list. In the next Chapter we shall discuss in detail how we can explain the origin of these different kinds of topography in harmony with the shearing net.

In closing the discussion of the evidence given by the topography, it may be remarked that no particular features have been found in the areas inside the stippled lines where we may expect that the shearing planes are not normal to the crust. So no light on this part of the theory could be obtained.

We shall now briefly examine the evidence provided by the geophysical data. For the North Atlantic they confirm in two ways the hypothesis of a net of shear planes intersecting the crust. In the first place the numerous volcanic islands showing a linear distribution of the volcanoes point in this direction, and in the second place the gravity anomalies show that these islands, as well as the submarine ridges, are probably not formed by crustal folding or buckling but that a system of block-faulting is more likely here [VENING MEINESZ, 1942]. As has been mentioned before, these results as well as the preponderance of two main topographic trends over the whole region have led to the undertaking of this investigation. In general we may say that our hypothesis gives a satisfactory explanation of the volcanism at the Earth's surface as far as it does not accompany tectonic action in orogenic areas.

Another area where the gravity results give evidence for our subject is the East Indian Archipelago (see Fig. 11). As has been set forth elsewhere [VENING MEINESZ, 1934, 1940], the field of anomalies in this area shows narrow belts of large negative anomalies probably disclosing a downward buckling of the Earth's crust; the belt shows folding and overthrusting of the layers at the surface. It is likely, therefore, that in these belts the crust is subject to strong horizontal compression and the direction of the compression can be derived from the anomaly field; it has an azimuth of about 160° east of north. This direction coincides remarkably well with one of the two directions of the shearing net, and so we may well suppose that this compression is caused by a movement relative to its neighbors of the crustal block comprised between the fifth and the sixth zone of the above list. The Net thus explains the direction of this major crustal phenomenon. In the above-mentioned publications [VENING MEINESZ, 1934, 1940, and 1942], the writer assumed an originally unbroken crust and attributed this direction to the direction of the compressive force working on the crust, but, in view of the present explanation, this force might have worked in a somewhat different sense, although a great deviation does not seem likely.

A further correlation to the Net is shown by the eastern half of the anomaly field. The two belts of negative anomalies, over east Celebes and over Timor, as well as a belt between the weaker positive anomalies than the neighboring basins show, are all parallel to one of the two directions, while two other belts, one over the southeastern arm of Celebes and one over the islands of Ceram and Obi, coincide with the second. It is also clear that if the most northern of the two belts of strong negative anomalies, that is, that over east Celebes, really represents a great horizontal shortening of the crust, this can only be explained by a shearing of the crust that allowed the crustal blocks on both sides of the belt to approach each other, whereas the parts to the west did not undergo any relative movement. It appears that this shearing plane is parallel to the second Net direction and, following the southeastern arm of Celebes, runs towards the Mangkalihat Peninsula of Borneo. This second Net direction appears likewise to play a part in the southeastern part of the archipelago, namely, in the direction of the twist of the southern belt of negative anomalies over Soemba and in the part of that belt running from the Kai Islands towards Ceram.

The topography of the East Indies also shows a clear correlation. Only a few lines of it have been included in our statistical investigation. We may mention here the west coast of Sumatra and the island ridge parallel to it as well as the main mountain ridge of Sumatra, the Boekit Barisan, the Palawan Island ridge with a part of the North Borneo Shelf in its continuation, the ridge of shoals running from Panay towards British Borneo, the Soeloe Archipelago, the two ridges running south of Mindanao with the Mindanao Trough to the east of them, the Mangkalihat Peninsula of Borneo, a second outjutting of the Borneo Shelf to the south of it, the eastern and southeastern arms of Celebes with the Toekang Besi Islands and the ridge connecting the Tiger Islands with the south arm, the ridges and troughs in the northwestern part of the Banda Sea, the northern arm of Halmaheira with the island of Morotai, the northeastern and southern arms of Halmaheira, the ridge between Ceram and the Kai Islands, the Lucipara Islands ridge and numerous other ridges in the same area, the ridge from Wetar to Seroea, the ridge from Timor via the Tanimbar Islands to the Kai Islands, and lastly the Australian Shelf. A more detailed study of the gravity field and the topography over the East Indies in connection with the shearing net may be reserved for a future occasion.

A great part of the West Indian area has also been surveyed gravimetrically, and a narrow belt of strong negative anomalies has likewise been found there [HESS, 1938; VENING MEINESZ and WRIGHT, 1930; BROWN and HESS, 1933], but the results are less complete and the study has not yet been finished. It is not possible, therefore, to draw conclusions about the direction of the compression, but it looks as if the problem is more complicated than in the East Indies; probably at least two directions are present. It seems likely that the South American Continent had a relative movement with regard to the block of the Caribbean Sea towards the north-northeast, that is to say, that its direction more or less coincides with one of the two net directions, but apparently this block itself moved towards the east-northeast with regard to the North American block, and this direction shows no correlation with the Net.

The topography also shows less correlation than in the East Indies. The Bartlett Trough and the Anegada Passage give the impression of being shear lines, and the gravity results are in harmony with this view, but their directions do not agree with the Net. Perhaps we can account for these deviations by the fact that they are situated in an area where the stresses caused by the shift of the poles are less than half of the maximum stresses, and that the corresponding shearing directions are, therefore, less predominant here. There are, however, several topographic directions in harmony with the Net; we may mention the following: East coast of Yucatan and Honduras, a line which begins in a ridge connecting the Galapagos Islands with Central America and which continues in the east coast of Nicaragua, the last one marked by the small islands and banks of Albuquerque Cays, St. Andrews Island, Old Providence, Quito Sueño Bank, and Rosalind Bank, and which perhaps finds a continuation in the edge of the shelf to the east of the United States up to New York; further the line of shoals about 250 km to the east of the small islands mentioned which continues in Windward Passage and Caicos Passage and perhaps in the Bermudas; the shelf line of the South American coast from the Gulf of Darien to Cartagena, which continues in the Beata Ridge and the coast of Hispaniola from Punta Beata to Azua; the ridge of the Lesser Antilles from Grenada to St. Lucia, and the parallel ridges to the west and the east of it; the different passages in the eastern Bahamas as, for example, the Turks Island Passage and the Caicos Passage, the Bonaire and Los Roques Trenches; the northeastern edge of the Bahamas Shelf and the length direction of the sounds in that archipelago; the shelf edges of the eastern and western coasts of Cuba; a line of shoal places running southeast from the west coast of Jamaica; and a few smaller features. Several of these lines have already been noticed by SONDER [1936-38] in a paper on "lineament tectonics" in this area.

As no sufficiently complete and detailed gravimetric surveys have been made in other areas where tectonic orogeny is going on in the present period, no further data about the direction of horizontal compression of the Earth's crust have been obtained in this way which could be compared to the directions of the Net.

An instance of a gravimetric survey disclosing the structural lines of an area in great detail, and thus providing the possibility of checking the correlation with the Net, is furnished by the new anomaly map of the Netherlands. This map has been compiled from the observations of the "Bataafsche Petroleum My," the Netherlands Government Mines, and the Netherlands Geodetic Commission, all made with instruments belonging to the first mentioned company. The great number of observations rendered possible by the rapid determinations with modern gravimeters permitted representation of the gravity anomalies in great detail. The map shows a striking predominance of the southeast-northwest direction in all the detailed subterranean structures and thus proves a strong correlation to the corresponding Net direction. This direction was well known in the southeastern part of the country where the block faulting along fault planes in this sense had already been investigated by numerous borings and by mining; it has now been proved to continue over the whole country. The geological interpretation of this map will not be entered upon here. It is curious to see that earlier gravimetric maps of the Netherlands, which were much less detailed, barely indicated this direction [VENING MEINESZ, 1923]; only the greater detailing brought it forth.

Another field of gravity results showing a clear correlation with the two directions of Net 1 is found in the western part of the Mediterranean. This area has been surveyed by the well-known gravity expeditions of Cassinis and De Pisa in the Submarine Vettore Pisani of the Italian Navy, of Marti in the French Submarine Fresnel, and of Pélissier in the Submarine Espoir, likewise of the French Navy. The results have been studied by COSTER [1945], who subjected them to an isostatic reduction of the Airy-Heiskanen type and of the regional type, both for a crustal thickness, T, of 30 km. Examining several gravity profiles, Coster comes to the conclusion that nearly everywhere the isostatic compensation has a local, or nearly local, character, which points to an area here of block faulting. In connection with this result we reproduce in Figure 12 the map of the anomalies found by the local reduction. We see that the whole western and northern part of this map shows two prevailing directions, northwest and northeast, which coincide remarkably well with the two directions of Net 1. This is especially noteworthy as the topography in this area does not show this correlation so clearly, as already mentioned. The gravimetric map seems to show better the courses of the faults between the different crustal blocks than the topography. Only in the southeastern part of the map, that is, in the area of Sicily and Calabria, the coincidence with the directions of Net 1 is less pronounced. We may remark, however, that here the crustal deformation probably has more the character of the geosynclinal type, as is indicated, for example, by the strong seismic activity in this area, and so deviations from the Net are not surprising.

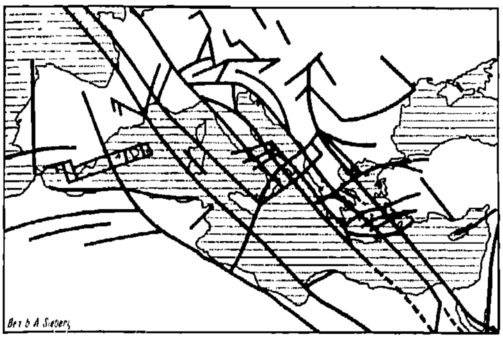


Fig. 13--Tectonic pattern of Mediterranean Region [after A. Sieberg]

Turning to the seismic evidence, we find nearly no deductions of positions of shear planes in earthquake centers that have a bearing on our problem. A number of these determinations have been made in Japan by Shida, Tanahasi, etc., but here the shear planes probably have their origin in tectonic phenomena; they do not coincide with the Net directions. One plane of shear corresponding to one of the two Net directions, along which movement is still going on, is well known, namely, the San Andreas Fault in California, which brought about the earthquake catastrophe of San Francisco; it is the longest fault plane observed on Earth. No determination of its position with regard to the vertical is known, however, to the writer. So, as yet, no conclusions from such determinations can be drawn about the slope of the shear planes of our Net with regard to the vertical. It is to be hoped that in the future data about this point will become available.

The other way in which seismic results may shed light on our problem, the deduction based on the situation of the earthquake centers and on the geological data of the planes along which the movement has been going on, has been especially taken up by Sieberg [see also HOBBS-RUSKA, 1910]. As the geology plays, however, a part in these interpretations, and as we shall refrain from discussing data from that side, we shall not consider this material; for this subject the reader may be referred to the publications of Sieberg [for example, his "Erdbebengeographie" in Gutenberg's "Handbuch der Geophysik," v. 4, 1932]. We shall only reproduce in Figure 13 the map Sieberg gives on page 769 of this comprehensive summary of the subject. Especially the southeast-northwest direction is clearly shown; the other appears in the east of Spain and in the eastern Mediterranean. Other instances of good correspondence may be found in the map [p. 710] for the western and northern parts of France, in the map [p. 719] of Central Europe, in many lines of the map of the Rhineland [p. 721], in the maps of Italy [p. 746], and of Corsica and Sardinia [p. 771], in the map of the Aegean Sea [p. 777], in that of China [p. 828], in those of South Africa [p. 892 and 897], in that of California [p. 942], and in fact in the majority of the maps of this publication.

Before leaving the subject of the correlation of geophysical phenomena and the shearing net of the Earth's crust we may briefly mention the curious relation to the Earth's magnetism pointed out by S. W. VISSER [1943]. In the first place the magnetic equator nearly coincides with the great circle where the critical stress is a maximum; this circle passes through the points where this stress has its maximum value indicated by 1.00 in Net 1, and from there it follows the diagonals of the Net compartments. In the second place the residual field after deducting uniform magnetization shows regional positive and negative areas more or less coinciding with the areas of minimum stress in Net 1 and with areas halfway between them. It is difficult to decide whether these coincidences are fortuitous. There is no doubt that further investigations of possible connections between the two phenomena would be worth-while.

As has been mentioned in the beginning of this Chapter, geologists such as Sederholm, Hobbs, Sonder, and others have found geologic and geomorphologic evidence in favor of the idea that a world-wide system of shear planes exists in the Earth's crust. They obtained indications of a few predominant directions, of which northwest and northeast are the most common, and they called these directions "lineaments." On page 225 of his comprehensive paper on this subject in the Eclogae Helvetiae SONDER [1938] gave a nomenclature in which he defined the word "lineament" as the prevailing direction in an area, whereas he proposes the word "linear" for a special plane in this sense and the word "zonale" as a narrow zone of such planes continuing over great distance (see, for example, Fig. 10). In this paper Sonder remarks that a northwest and northeast direction can not be predominant over the whole Earth's surface, because in that case the shear curves should have to be loxodromic and this does not appear likely; for the polar areas, for example, it would lead to absurd consequences. He concludes, therefore, that it can not be more than a rough approximation and he finds, in fact, somewhat different directions for different areas. From the viewpoint of our hypothesis this becomes clear; for a great part of the inhabited regions of our Globe Net 1 shows, roughly speaking, northwest and northeast directions, but they differ for different areas and for the polar regions they are entirely different.

In this same paper Sonder deals also with the question as to what period these shear planes can have originated, and he expresses the opinion that they must be very old; he thus came to the same conclusion as the writer, and the fact that the continental coasts seem to show a correlation does not indeed appear to admit any other view. Sonder also points out that the fact of fairly recent sedimentary layers showing the effect of the shearing does not mean that these shear planes must be younger than the sediments; it only proves, in fact, that in recent times new movements along these planes must have taken place. It is clear that all forces working on a crust intersected by shear planes are indeed likely to give rise to such movements.

SONDER [1938, p. 212] attacks the problem of how the existence of shearing planes in the crust can bring about the topography which at the Earth's surface seems to accompany their presence. We shall examine this question in detail in the next Chapter, where we shall mention Sonder's valuable contributions to the problem. In this Chapter we shall deal with the evidence given by him and other "lineament" geologists for the presence of shearing planes in the crust.

One of the Continents where this evidence is clearest is Africa. KRENKEL'S map [1925], reproduced in Figure 14, as well as the one given by SONDER [1938, p. 208] clearly show two systems of lines which nearly coincide with the two directions of our Net. We may also reproduce here a chart of the Gulf of Aden (see Fig. 15) which has been compiled by TH. STOCKS [1941] from recent maps and soundings. It shows a series of ridges and troughs fitting perfectly in the general picture, their direction coinciding exactly with one of the two Net directions; the area of this map has been included in the measurement of the Indian Ocean. The two African directions are also evident in KRENKEL'S map [1922] of the Graben zones in east Africa. It seems probable that this whole last area has been subject to tension in an approximately east-west sense and that it, therefore, has a length direction in a more or less north-south sense, but the great majority of the faulting occurred in two directions about coinciding with those of the Net. It may be that the east-west tension itself has been caused by the shift of the poles--the Formulas (13) of Chapter II, in fact, indicate tension in this sense here--but as the Graben formations are much younger than we supposed for the polar shift, it seems more likely that other forces are responsible for it.

The good correspondence of practically the whole African Continent with our shearing net adds 29.8 million km^2 to the part of the Earth's surface showing a correlation to the Net. It thus brings the figure of page 35 up to 279.4 million km^2.

For Europe there is also a great deal of evidence. The earliest investigations of this kind have been made by DAUBRÉE [1880]; they show, for example, a northwest lineament in the watercourses of northwestern France [SONDER, 1938, p. 201]. For Scandinavia and Finland SEDERHOLM [1913] has collected extensive material, of which we reproduce the map of the Päijänne See in Finland, which shows unmistakable evidence of faults in a northwest direction (see Fig. 16), and the map representing the watercourses and fault lines in the whole of Fennoskandia (see Fig. 17). This map shows a strongly predominant northwest lineament over nearly the entire area, and this corresponds to one of the two directions of the Net. The second direction is less generally represented,

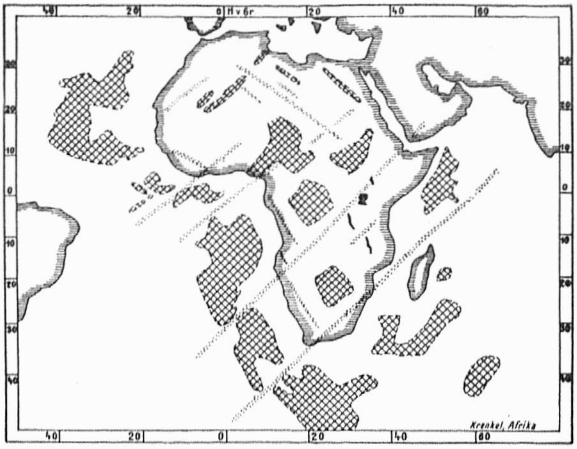


Fig. 14--Tectonic patterns for Africa and neighboring oceanic basins [after E. Krenkel]

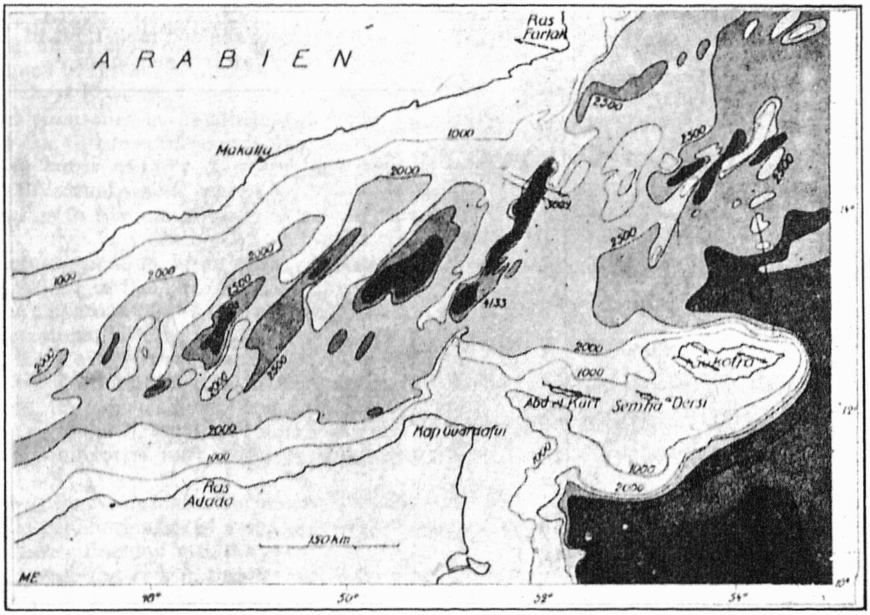


Fig. 15--Chart of Gulf of Aden showing series of ridges and troughs [after Th. Stocks]

but we find evidence of it in the area along the west coast of Norway from Stavanger to latitude 66° north and perhaps also in the western half of southern Sweden, although here the prevailing direction deviates a great deal more than 12° from this direction. In his paper in the Eclogae Helvetiae SONDER [1938] mentions also the work of Kaufmann in Gotland and Öland, represented in fault roses for each of these islands; the first island shows two preponderant directions in exact harmony with the Net, and those in the second deviate only slightly.

An interesting example is also given by SONDER [1938, p. 207] in a map of the upper Rhine Graben (see Fig. 18), which shows that the smaller faults on both sides of the Graben are in better harmony with the northeast direction of our Net than the main direction of the Graben itself. It appears that these smaller faults may be attributed to the original polar shift and it is reasonable to assume that the Graben formed by other more recent causes has only partially

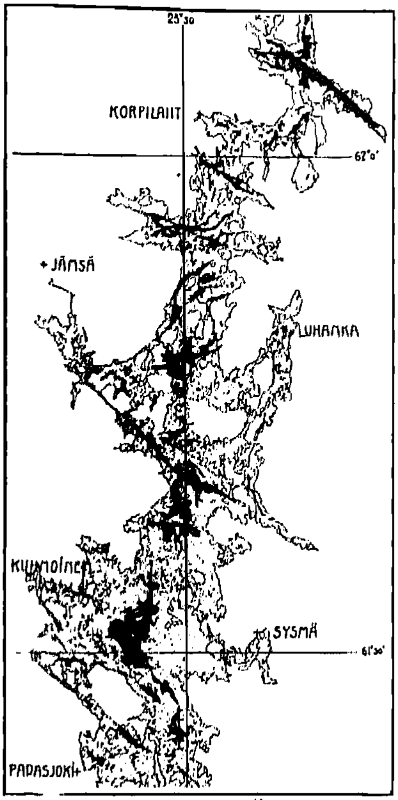


Fig. 16--Map of Päyänne Lake, Finland, showing fault pattern [after Sederholm]

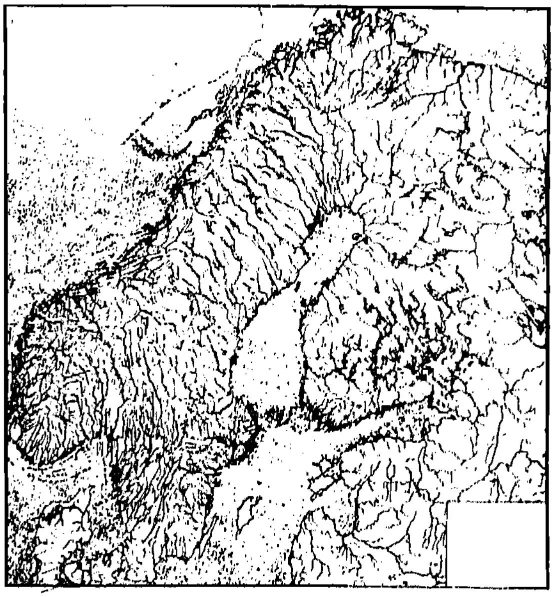
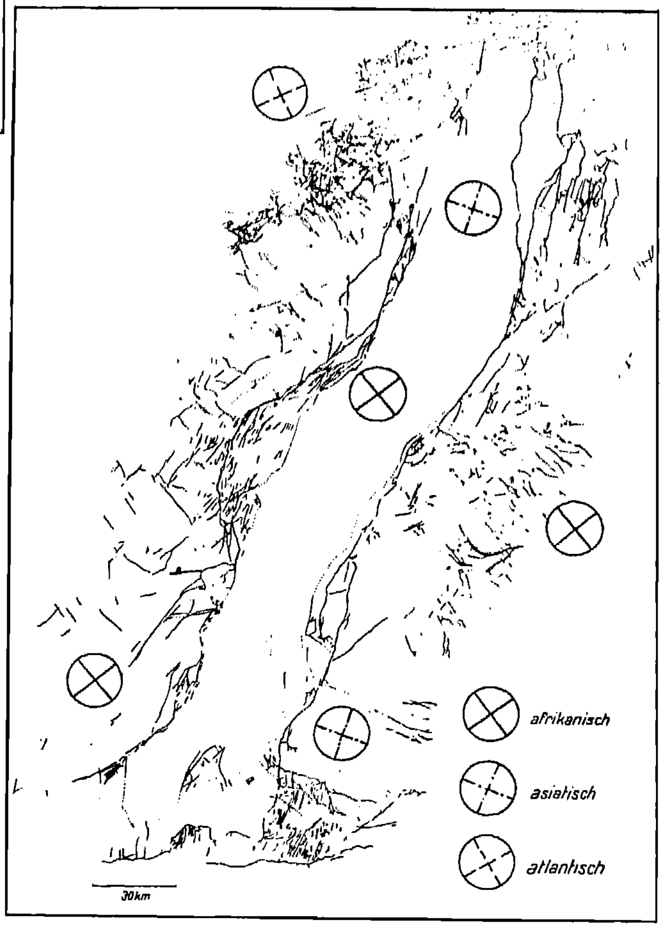


Fig. 17--Water courses and fault lines of Fennoskandia [after Sederholm]

Fig. 18--Fault patterns of upper Rhine Graben [after Cloos, modified by Sonder] ⟶



followed the old faults. The fault roses added by Sonder show the differences in the directions attributed by him to different areas.

SONDER [1938, p. 219] gives a map of the Aegean in which he traces two predominant directions practically coinciding with those of our Net and each occurring in many lines; this interpretation agrees with that given by Sieberg as mentioned above; the northwest direction, moreover, is also preponderant in many structural lines of the Balkans.

In all these European areas the directions are in harmony with our Net. If we add to this the clear geophysical evidence for the Netherlands and the well-known faults of Scotland, which are likewise in agreement with it, we may conclude that as far as it goes the evidence for Europe supports our hypothesis; the above-mentioned correlation of the topography in Central Europe and in the Mediterranean Area are further assets. It may be hoped that in the future more geological checking will be forthcoming.

For the North American Continent material has been collected by HOBBS [1911], who was one of the first geologists giving his attention to the problem of fracture nets, and who has given a valuable summary of instances. The North American examples do not agree in quite the same measure with our Net as those in Africa and Europe, although in several cases at least one direction, and sometimes both directions, coincide; in one of the clearest cases of lineaments--in Western Ontario near Timiskaming Lake--both directions, for example, are well in harmony with it (see Fig. 19). A lesser agreement is not surprising in this Continent, because in a great part of it the stresses caused by the shift of the poles are so small that no shearing effect can be expected. In those areas other forces working on the Earth's crust do not find prepared fault planes, and so shear must occur in directions connected with these forces, while, in areas where the polar shift has brought about shearing, the effect of later forces will in many cases occur along the older planes. Since in the northwestern part of North America the shift of the pole must have given rise to greater stress, we may here expect a stronger correlation with our Net and the two examples of lineaments mentioned by SEDERHOLM [1913, pp. 25ff] in this area, the fault valleys near San Francisco and the area of Jakutat Bay in Alaska give indeed coinciding directions. Figure 20 represents the latter of the two, where both directions of the Net can be recognized--the north-northwest direction among others for the coast line of Jakutat Bay and in Russell Fjord and the west direction in Nunatak Fjord and in other lines.

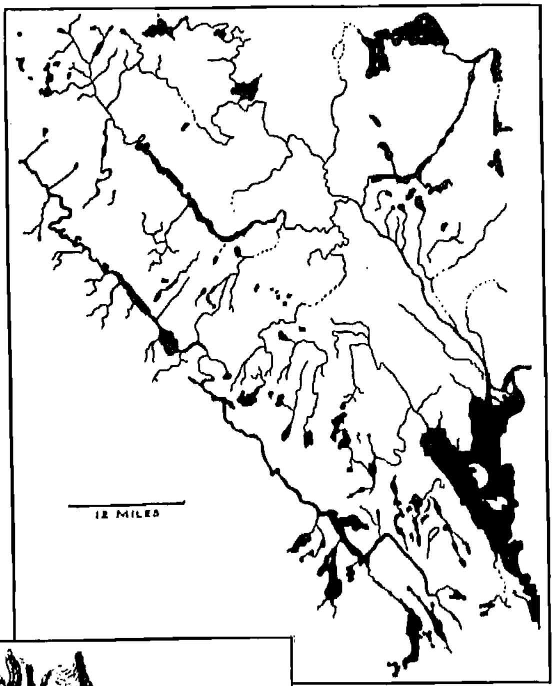
[In September 1946, after the preceding paragraphs were written, the author had a discussion with J. T. Wilson of the University of Toronto about an extensive study he is making of the trend-lines in the Canadian Shield, mostly using the topographic indications shown by air maps and other topographic maps. Where possible he has compared his conclusions with the geological data and has found them everywhere confirmed. The results of his investigations give a striking corroboration of Net 1. In the whole area east of the meridian of 90° west, also comprising the major part of Labrador, the correlation is about 95 per cent, and in the area west of this meridian extending to the areas around Great Slave Lake and Great Bear Lake it is 60 to 70 per cent. These results cover nearly the entire northern part of the North American continent east of the Rocky Mountains.]

For the other continents not much is known. For the southern part of South America, WINDHAUSEN [1918] has indicated a system of two fracture directions (see Fig. 21) of which the northwest direction coincides with the corresponding direction of our Net, whereas the second slightly deviates, but for the rest of this Continent no data are known to the writer. The same is true for Australia, while for Asia only a few short remarks are given by SONDER in the Eclogae Helvetiae of 1938; on page 205 he mentions that AHNERT [1926] has found a northeast orientation and smaller northwest fractures in Eastern Asia and that Tongking shows a northwest lineament, and on page 206 northwest and northeast orientations for the western border of Asia. All these directions seem to be in harmony with our Net, but more details are required before we can attribute weight to this agreement.

We may conclude that the material hitherto collected by the lineament tectonicians gives positive evidence in favor of our hypothesis in Europe and in Africa and a little elsewhere. Contrary evidence has not yet been obtained. It is true that also north-south and east-west lineaments have been mentioned, but these directions are less frequent and their number is not sufficient to permit the conclusion that they occur systematically over a great part of the Earth's surface. In the suboceanic topography, moreover, no evidence for these directions has been found. As far as can now be decided, these directions may be fortuitous and may be caused by forces of a regional character; there is no need yet to look for another planetary effect that could explain them.

The result of our investigation in this Chapter is that the evidence collected over more than half of the Earth's surface is decidedly in favor of our hypothesis. It does not seem likely that

Fig. 19--Drainage map, part of District of Nipissing [after W. H. Hobbs] ⟶



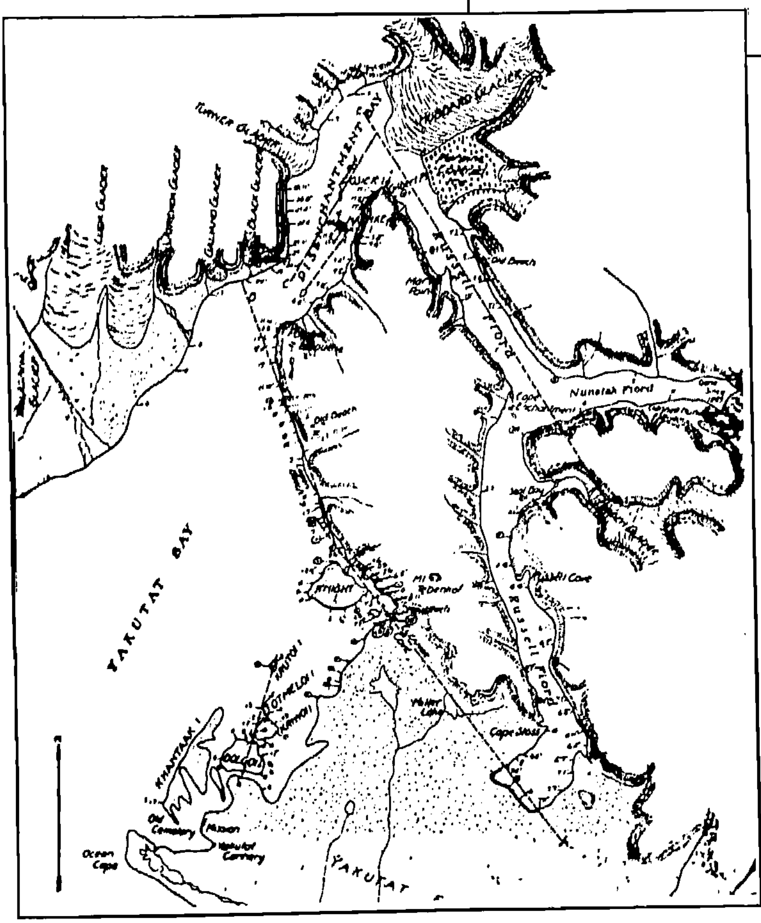


Fig. 20--Jakutat Bay, Alaska ⟵ [after Tarr and Martin]

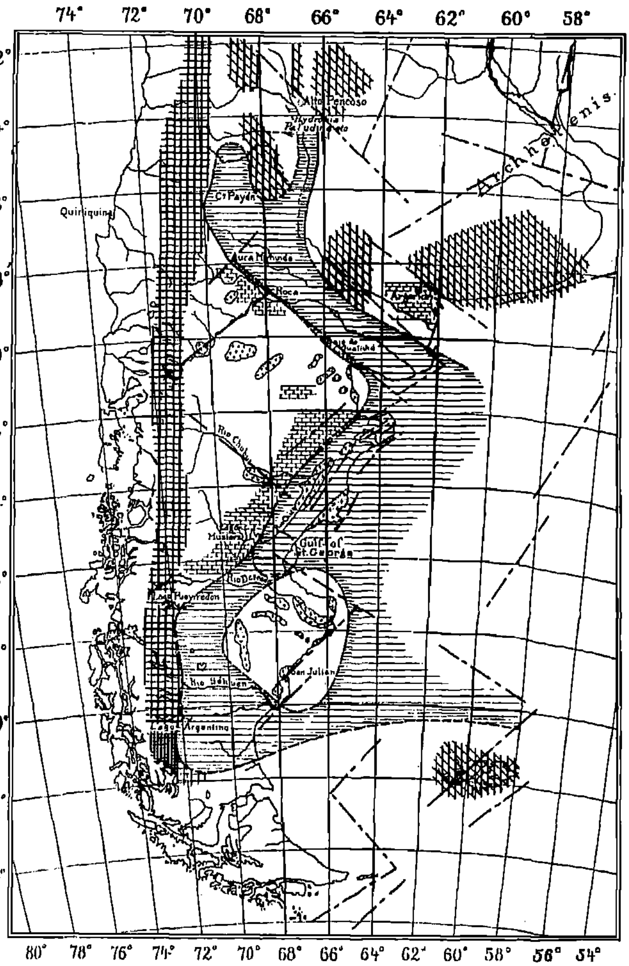


Fig. 21--Sketch map showing prevailing direction of joint fissures, southern South America [by W. H. Hobbs after A. Windhausen]

another phenomenon could account for the great number of coincidences with our Net that have been found.

The question now presents itself at what date the shift of the poles could have taken place. If we admit that the correlation with the continental coasts has a real background, we must suppose it to have taken place before the shelf edges came into being, that is, in one of the earliest periods of the crust's history. If we should neglect this coastal evidence, we should still have to assume it to be old; the correlation of our Net with the trend of the variscian orogeny would compel us to suppose it at least Pre-Carboniferous. As there is hardly reason, however, to put aside the coastal correlation, we may consider a much older date as probable.

This result has an important bearing on geophysical theories. As the net of shearing brought about by the polar shift can only have originated in a closed rigid shell over the whole Earth's surface, every hypothesis assuming horizontal displacements of the continents over great distances in periods previous to the shearing would have to be abandoned. This is likewise inevitable because of the fact that such displacements must have so much disturbed the net of fault planes, that the correlation would have disappeared over large parts of the Earth's surface. We may conclude that Wegener's well-known theory is not compatible with the hypothesis advocated in this paper.

We may draw two more conclusions from our results. In the first place they confirm the picture of a rigid crust floating on a plastic substratum, a picture first introduced by Airy to explain isostasy, and which was further supported by the extension to the case of regional isostatic compensation on the basis of a floating crust bending under the effect of superimposed loads [VENING MEINESZ, 1939 and 1941 a]. This picture was also confirmed by the studies of RUSSELL [1939] on the Mississippi Delta, of VENING MEINESZ [1941 b] on Hawaii, etc., and of SAURAMO [1939] on "the mode of land upheaval in Fennoscandia during late-Quaternary time." It is likewise in harmony with the theory of crustal buckling given to explain the belts of negative anomalies in the East and West Indies [see Chapter IV]. The hypothesis dealt with in this paper gives it a further support. This purely mechanical view of the crust's behavior is no doubt not complete; it is to be expected that other phenomena, as, for example, chemical processes, differentiation, and metamorphism, also have played a part in the history of the crust.

In the second place it is interesting to notice that the evidence in favor of our Net of fault planes gives support to the idea that we may apply the hypothesis of BYLAARD [1935, 1936], further elaborated by Van Iterson, to the case of deformations in the Earth's crust. Bylaard himself has already affirmed this in papers concerning the crustal deformations in the East Indies. A more thorough investigation of this question, which seems of great importance for the geophysics of the Earth's crust, is worth while. It may be reserved for a future occasion.

CHAPTER IV

The Effect on the Topography of Fault Planes in the Crust

The main evidence in Chapter III favorable to the existence of a world-wide shearing net in the Earth's crust is the correlation the topography shows with our Net over a great part of the Earth's surface. In order to make this evidence valid, it is necessary to indicate how the presence of shear planes in the crust may bring about topographic features--the problem investigated in this Chapter.

For this purpose we shall successively study the effect of volcanism, isostatic effects, vertical or epirogenic movements, the effect of horizontal stresses in the crust, orogenic deformations such as buckling, folding, and overthrusting of the crust and its layers, the effect of erosion, and the effect on the course of rivers and smaller water courses. For several of these agents new viewpoints will arise from the supposition of pre-existing shear planes in the crust; this will be especially the case for the orogenic phenomena. At the end of Chapter IV we shall discuss the problem of how a correlation of the shearing net with the borders of the continents can perhaps be explained.

Before starting this investigation we have first to see whether the origin of these shear planes itself already can have given rise to topographic features. If we assume that the shearing of the crust occurred through plastic flow in narrow zones so situated that the length dimensions of these zones do not change, the dimensions at right angles to the crust can not remain unaltered, and so movements of the Earth's surface in a vertical sense may indeed be expected in these zones. We shall try to determine the topography which in this way may come into being. For doing this we first derive the component of the deformation at right angles to the crust on the supposition that the whole crust has been subject to plastic flow under the effect of the stresses given by Formulas (13) of Chapter II. The shortening, ϵ, in the crust of a unit of length of the normal to the crust's surface in the case of plastic flow, that is, for m = 2 is given by

$$\epsilon = (\sigma_\delta + \sigma_\alpha)/2E = [2m/(5m + 1)]\beta \sin\theta \sin^2\delta \sin(2\alpha - \theta) \quad \text{.........} \quad (49)$$

Assuming that the part of the crust considered has not yet reached isostatic equilibrium, the rising at the surface would be $\delta h = -(1/2)T\epsilon$, in which T is the thickness of the rigid crust. If, on the contrary, the readjustment has taken place, we find for the usual assumptions of 2.67 and 3.27 for the densities of the crust and of the plastic substratum $\delta h = -0.1835T\epsilon$.

Returning to the hypothesis that flowing occurs only in narrow strips of the crust, and assuming that these strips represent a part of the Earth's surface denoted by the small quantity μ, we find that if in the remaining part of the crust the stress entirely disappears, the whole deformation is concentrated in the strips and that, therefore, their rising with regard to the other parts of the crust is given by (50).

$$\delta h = -0.1835T\epsilon/\mu \quad \text{.......................} \quad (50)$$

If the stress does not entirely disappear in the remaining parts of the crust, the value of δh is correspondingly smaller.

In Formula (49) we have to introduce the value of m for elastic deformation because the stress distribution in the Earth's crust is practically determined by the elastic stresses and so we shall put m = 4.1; the first factor of Formula (50), moreover, does not vary much for another value of m. Introducing $\beta = (1/297)$, $\theta = 70°$, T = 30 km, and a rather arbitrarily chosen ratio $\mu = (1/20)$ we obtain for isostatic readjustment

$$\delta h = -133 \sin^2 \delta \sin (2\alpha - \theta) \text{ meter} \quad \text{(51A)}$$

and in case isostasy has not been established

$$\delta h = -362 \sin^2 \delta \sin (2\alpha - \theta) \text{ meter} \quad \text{(51B)}$$

So we see that the elevation or depression, thus coming into being in the deformed strips, is small; in the more probable case that the isostatic equilibrium has been readjusted, it varies over the Earth's surface between + 133m and - 133m. The map of Figure 22 shows the value of minus the variable factor of Formula (51), which has to be multiplied by 133m or 362m to get the rising of the Earth's surface in the strips.

It is hardly probable that remnants of such features are still present. It is hardly necessary to say this seems out of the question on land where, if they have indeed existed, erosion must have worn them off or sedimentation filled them long ago, but in submerged areas it also seems unlikely, because since those very early periods, in which we assume the shearing to have taken place, we must expect considerable sedimentation, even in the deep oceans, and so probably all evidence must have been hidden. The cross sections of the ridges or depressions which might have been brought about are not easy to predict; we can only say that the area of the cross sections must have corresponded to the product of the elevation δh by the horizontal dimension of which the mean value in a certain area is given by the ratio μ. As the course of the strip, however, under the effect of irregularities in the physical properties of the crust must no doubt deviate from the straight course, and as the relative movement of the crustal parts on both sides of the strip must have had a component parallel to its general direction, the horizontal dimensions of the ridges and depressions must have varied accordingly.

We shall now proceed to examine other effects that may have brought about changes in topography. Some of these effects must have acted as a direct consequence of the shearing, whereas others, as, for example, the orogenic phenomena, may have occurred long afterwards, but as these last occurrences must have been altered by the presence of the shearing planes in the crust, they must also have given rise to a topography correlated to our Net. We shall begin with the more directly connected phenomena; in many cases, however, later effects may be mixed up with them.

In the first and most important place we may mention the volcanism which the shearing of the crust must have brought about. It is clear that even if this shearing has taken place in the shape of plastic flow in a thin layer along a narrow belt of the crust, it must have released plutonic action in this layer, which in many cases must have come to the Earth's surface. This plutonic and volcanic activity must no doubt in many areas have continued up to the present time, as other forces working in the crust must have made the shear planes alive again and thus have reopened the magma passages. The distribution of the volcanoes over the Earth is well in harmony with our supposition. It has been generally recognized that the volcanoes may be brought under two headings, those occurring in orogenic belts and those situated elsewhere. The first, usually called of the "Pacific" type, are characterized by calc-alkaline magmas, while the others of the "Atlantic" type develop alkaline effusives [KENNEDY and ANDERSON, 1938]. We must expect the shear planes of our Net to produce the latter type, and this seems indeed to be true. These latter volcanoes often occur in straight rows, for example, in several oceanic islands, as Pico with Fayal, San Jorge and San Miguel in the Azores, and this has been explained, no doubt rightly, by the supposition that they are caused by fault planes in the crust. As far as the writer knows these rows are all in harmony with the Net, and as for the other volcanoes of this type, they are often accompanied by topographical features, as, for example, submarine banks, in line with the volcanoes, the directions of which likewise coincide with the Net. For the volcanoes of the calc-alkaline type this is not so generally true, although there are many instances of good concurrence. It is clear that this can be explained by the fact that these volcanoes occur in orogenic belts, and that the strain in the crust during the great tectonical phenomena in some cases may have been relieved by shear along the planes of our Net, but in others must have formed new fault planes in other directions.

Another point in favor of our hypothesis is that the volcanoes of the alkaline type occur especially in those areas where the stresses, as our map indicates, are larger than three-quarters of the maximum value, and where the movement along the shear planes must have been correspondingly great. This is striking for the Atlantic, where, for example, the situation of Iceland in the narrow zone of strong stress is noteworthy. Only the Bermudas, which probably also have a volcanic origin, are situated outside. It is likewise true for the Pacific, where only a few islands, namely, Easter Island, Sala y Gomez, Juan Fernandez, and the Galapagos Islands, are situated in the southeastern part, in an area of smaller stress. It is not certain, however, whether the volcanoes of these islands indeed belong to the normal alkaline type; they do not produce nepheline-bearing effusives, and they are not grouped in linear rows, as are nearly all the other Pacific islands east of the andesite line. The volcanic islands of the western Indian Ocean seem also to form an exception, but here again it is doubtful whether these islands belong to the alkaline group; some of them may perhaps be connected with tectonic phenomena, and the curved shape of the ridges seems to point in this direction. The Seychelles, moreover, show granites and syenites, Réunion feldspar basalt, gabbro and peridotite, and Mauritius a basement of diorite and schist, and so the ridge connecting these islands does not seem to belong to the alkaline type. The same is probably true for the Kerguelen Islands, where especially plagioclase basalt occurs.

The fact that thus a great part, if not all, of the Earth's volcanism in non-orogenic areas may be accounted for by our hypothesis appears to give it a valuable support.

We must expect that the topographic features caused by the volcanic action along the fault planes of our Net must be rather irregular. The unevenness of these planes in connection with the relative movement of the crustal blocks on both sides with regard to each other must have brought about fissures, or at least decrease of pressure, at irregular intervals in these planes, and so the volcanic outbursts must have varied considerably in these zones. We may expect, therefore, that the ridges thus originating must have a greatly varying height and breadth, and that they may even be entirely interrupted in some parts. This is in good harmony with many of the ridges in the Atlantic and Pacific Oceans, as far as we can judge from the charts derived from the many recent sonic soundings. Instances of these irregularities may be found in the ridge connecting the Gorringe Bank with the Portuguese Coast, the ridge running southwest from the islands of Fayal and Pico, the ridge connecting Terceira and Graciosa, the ridge running southwest from the Josephine Bank, the ridges of the Sandwich Islands, and many others. As other topographic formations attending the planes of shear in the crust must be more regular, it seems probable that the greatest part of the submarine topography correlated to our Net in these oceans has come into being by volcanic action.

The irregularities in the fault planes mentioned above must no doubt also bring about volcanic outbursts, which are possible not only if there is no component of the relative movement of the crustal blocks away from each other, but also in those areas where this movement has a component towards each other. This is the case for the areas of positive values in the map of Figure 22. We may, however, expect a smaller number of volcanoes in these areas than elsewhere, and this is confirmed by the facts. This may explain the scarcity of volcanoes in the Arctic and Antarctic regions.

In Chapter III we have drawn attention to the viewpoint that the great number of shear planes in the crust may be explained by an analogy to the experiments with steel strips subjected to tension above the elastic limit. In these experiments, after a first zone of flowage has come into being, hardening intervenes and the deformations do not continue in this zone. A second zone forms and in its turn stops deforming, and this goes on until nearly the whole strip is interlarded by zones of flowing. If the tension further increases, breaking sets in at last in one of these zones. After shear has begun to occur in the crust, magma must rise at once, and it seems probable that the cleavage may thus be sealed up and continuation of the shearing prevented. A second plane of shear must then be formed, and so we see an analogous process to the hardening of the steel taking place in the crust, but on an infinitely bigger scale. In this way the formation of a great number of shear planes in the Earth's crust can be explained which otherwise seems difficult to understand. The process may no doubt continue up to the present time; forces working in the crust must still give rise to movements along the planes of weakness, but at any moment magma intrusions from below, eventually leading to volcanic outbursts at the surface, may increase the resistance in this zone and thus give rise to the stopping of the movement and possibly to the coming into action of other zones of weakness.

The question may be put what anomalies of gravity we may expect to find over volcanic topography caused by the presence of shear planes in the crust. If we assume that the fissures of the crust have been completely sealed by the magmatic material and that the crust acts, therefore, as an unbroken elastic plate, we can consider the volcanic topography as an excess of matter superimposed on this plate and causing it to bend. The result is that the isostatic compensation must be distributed according to the hypothesis of regional compensation [VENING MEINESZ, 1939, 1941 a], that is, in broad flat roots formed by this bending at the crustal boundaries where the density shows a sudden increase. So we may expect that the anomalies will more or less disappear by regional isostatic reduction. The gravity results found over the Hawaiian Archipelago, over Madeira [VENING MEINESZ, 1941 b], over the Bermudas, and over St. Vincent (Cape Verde Islands) confirm this supposition; in general the radii of 174.3 km or 232.4 km give the most satisfactory results. The anomalies over the Azores Area and over some of the submarine banks of the North Atlantic, such as the Josephine Bank, show more irregular figures [VENING MEINESZ, 1942]; for some of the gravity profiles the regional isostatic reduction with varying radii provide the smallest anomalies, whereas for others in the same areas the local reduction meets the requirements better. The explanation seems easy; probably some of the shear planes in these areas have not been sealed and so the crust must react as a mosaic of crustal blocks carrying the volcanic loads and partially bending down and partially sinking in locally under their effect [VENING MEINESZ, 1942].

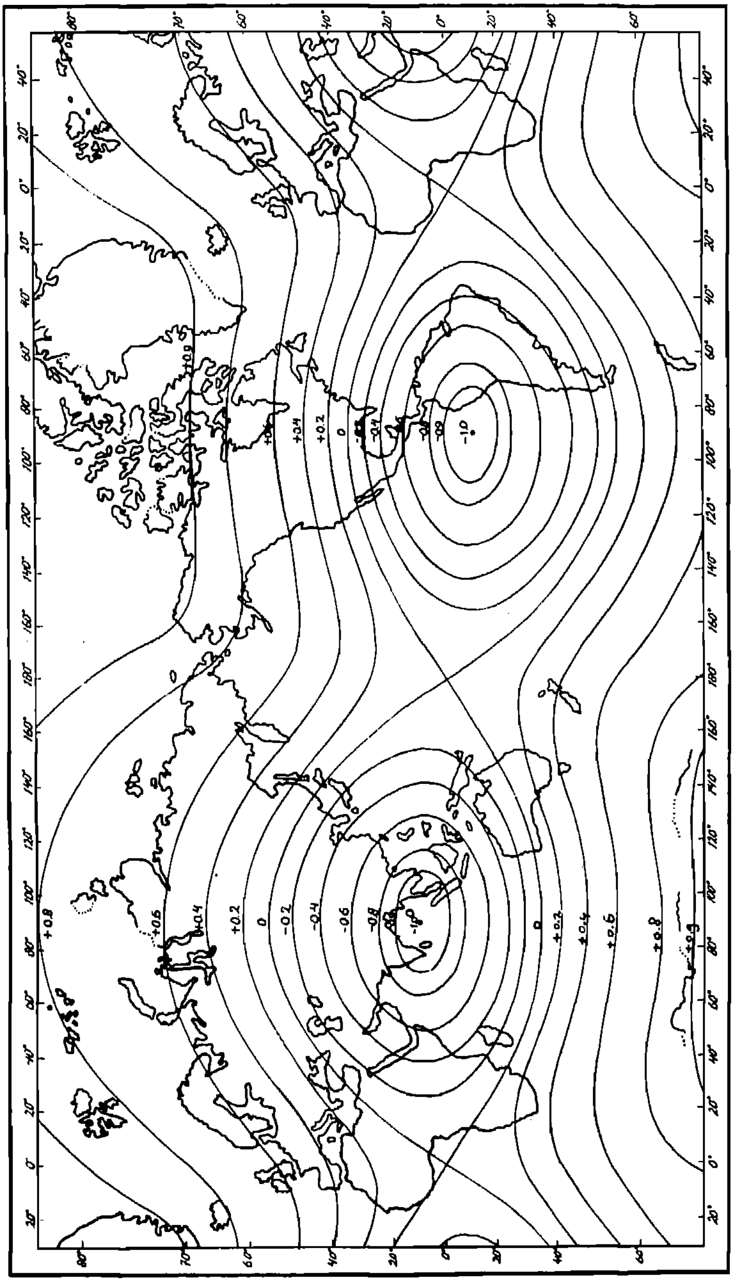


Fig. 22--World map of values of $(\sigma_\delta + \sigma_\alpha)$

A more detailed study of these questions and problems will appear in "Gravity expeditions at sea," v. 4 (to be published soon by Ned. Geod. Com.)]. Thus the gravity results found in the North Atlantic are in good harmony with our hypothesis of a system of shear planes and a volcanic topography superimposed on the crust.

As already mentioned the volcanism brought about by the shearing of the crust is probably the main cause of the topographic features correlated with the shearing net. We shall now proceed to other possible effects. In the first place we can affirm that shear planes not normal to the crust must lead to isostatic adjustments of the kind STEPHEN TABER [1927] first noted, at least if tension in the crust provides room for these crustal movements. As Figure 23 shows, two fault planes converging downwards must lead to the formation of a Graben, whereas diverging planes must bring about a ridge. In the same way parallel planes must give block tilting (see Fig. 24) and one plane a fault escarpment. If, on the contrary, the crust is subjected to a horizontal compression, the reverse must come into being; the formations to be expected in this case are represented in Figure 25.

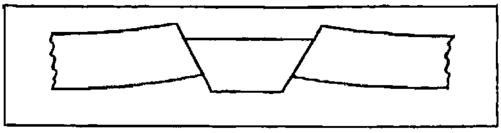


Fig. 23--Converging fault planes under tension producing a Graben

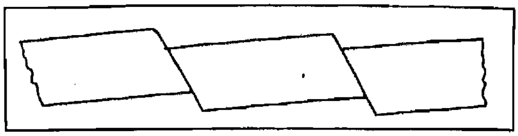


Fig. 24--Parallel fault planes under tension producing block faulting

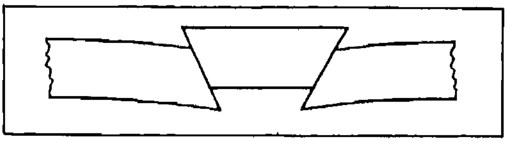


Fig. 25--Converging fault planes under compression producing a horst

If the shear planes formed by the shift of the poles concur exactly with the theoretical deductions, planes at relatively small distances from each other must practically be parallel, and so only block tilting and escarpments would form. These formations would then be limited to the areas of tilted shear planes, as indicated by the stippled curves in our Net, while the areas of vertical planes would have undergone no change. The process may be expected to have started at once after the shear had occurred for those areas where tension or compression was brought about in the crust in a direction at right angles to the direction of the plane. These areas may be derived from Figure 22, which shows the relative intensity of these stresses; in this Figure the positive sign corresponds to compression and the negative to tension. The forming of these escarpments must have continued in all areas, however, where a tensional or compressional stress has been working since. An instance of a formation of this last type may perhaps be found in the sinking away of the coast ranges of the Andes, which between Payta and Arica follow the directions of our Net. In this same direction STEINMANN [1929] supposes a continuation of these ranges to the northwest of Payta which would likewise have foundered. In this whole area the shift of the poles must have caused tension, but as the sinking must have been more recent it seems more likely that it has been brought about by other phenomena.

We have hitherto assumed that the position of the shear planes corresponded exactly to our deductions. It is clear, however, that the irregularities in the crust may well cause deviations, and so we need not exclude the possibility of other positions and of converging or diverging planes at short distances from each other, even if we adhere to our Net as far as the directions in the plane of the crust are concerned. Fairly recent crustal formations caused by such shear planes may perhaps be found in the East African rift valleys and in the coastal strip of Western Australia. The first are situated in the area where the shift of the poles must have given tension, and so these formations might even have started at that early date. The majority of these rifts follow the directions of our Net or do so with a slight deviation. Views vary about the question whether they are caused by tension or by compression. The gravity results found by BULLARD [1936] in his important investigation of this area led him to suppose compression, but most geologists still favor tension. As Figures 23 and 25 show, the shear planes must, in the first case, have diverged downwards and, in the second, have converged.

In Western Australia the escarpment of the Darling Range may perhaps also be attributed to the existence of a tilted shear plane combined with tension or compression. It must have been recently formed by the sinking of the coastal strip to the west of it. Probably the process is still active in the present period. As the writer had the occasion to investigate, the gravity field shows a curious deviation near Perth; he found strong negative anomalies over the coastal strip. [A discussion of these anomalies will soon appear in the publication above mentioned.]

The instances of topographic features mentioned above have all originated, no doubt, in much more recent periods than that in which we supposed the shift of the poles to have taken place. It is difficult to say whether there are still features present formed by the crustal catastrophe itself. For the effects we shall further discuss--the epirogenic and tectonic phenomena and erosion--this possibility does not exist; they are based on other forces working on the crust after the shear planes had come into being.

For the first, no long discussion is necessary. It is clear that epirogenic, or in general vertical forces exerted by the substratum and varying in horizontal sense, must give different displacements to crustal blocks separated by shear planes, and so escarpments along the lines where these planes reach the surface must in many cases have come into being. It will be difficult to recognize these formations in the submarine topography, but for the land topography we may perhaps be able to identify them, although even in this case it will not always be easy to distinguish between epirogenic causes and the effects of tension or compression in the crust as dealt with above. The few examples given for these last effects may likewise have been brought about, of course, by vertical forces exerted by the substratum.

The second cause of topography correlated to our Net--the effect of tectonic phenomena--will require a longer discussion. We shall base it on the hypothesis made in consequence of the finding of narrow belts of negative gravity anomalies in the East and West Indies, according to which, in the zones of tectonic folding and overthrusting of the surface layers, the major part of the crust is thrust downwards in the substratum in the form of a narrow root. This hypothesis suggested by the writer [VENING MEINESZ, 1930] has since found more and more support. We may mention here the investigation of the geology of the East Indies by Umbgrove, who found the supposition confirmed that these belts coincide with the areas of strong lateral compression of the surface layers [VENING MEINESZ, UMBGROVE, and KUENEN, 1934]. Special mention may likewise be made of the experiments of KUENEN [1936] with a layer of wax and paraffin floating on water and horizontally compressed; the layer, after a critical limit of the compressive force had been reached, began to show waves, and after some time one of the lower waves started pushing farther downwards and a local root came into being. These results proved to be in harmony with the theoretical treatment of the problem which shows that the phenomenon may probably be best understood as a kind of buckling of the floating crust after a critical stress has been exceeded [VENING MEINESZ, UMBGROVE, and KUENEN, 1934, pp. 44 ff and 117 ff; VENING MEINESZ, 1940]. Further support of the hypothesis was given by the following conclusions of others: By BUCHER [1933, p. 210] made on other grounds, which also suppose the origin of crustal roots in orogenic areas; by the study of KENNEDY and ANDERSON [1938, pp. 24-82] on "Crustal layers and the origin of magmas," in which they show that the volcanism in orogenic belts can not be understood without assuming the thickening in those belts of the crustal layers; by the studies of BYERLY [1938] on the Sierra Nevada, where he shows how the seismic results in California confirm "the great depth of penetration of the mountain mass" relative to the crust in the neighboring areas; by the interpretation by HESS [1938, pp. 71-96] of the gravity anomalies in the West Indies, where also a narrow belt of negative anomalies was found; by the study on mountain building by GRIGGS [1939], who made experiments on the formation of crustal roots by the action on the crust of subcrustal currents descending under the orogenic belt; and by the investigations and papers of many other writers.

Starting from the crustal-buckling hypothesis we shall first examine the theoretical problem of how the buckling process is affected by the presence of a fault plane. We must assume that at this place the crust can not resist bending in the same way as elsewhere, and in this connection we shall start from the assumption that no such resistance is at all present. This means that in a strip of the crust crossing the fault plane at right angles a hinge occurs at the point of intersection, or, in other words, that the momentum M of the stresses in a cross-section of this strip taken with regard to the horizontal middle line of the section is zero for a cross section through the fault plane.

Simplifying our problem by neglecting the Earth's curvature we have to derive the deformations of a floating plate of constant thickness T and infinite dimensions divided into two parts by a hinge line and subject to compression in a direction at right angles to the hinge line. It thus becomes a two-dimensional problem. Following the same line of solution as in an earlier paper [VENING MEINESZ, 1940, p. 285] we shall choose the X axis in the plane of the plate and the Y axis vertically downwards with the origin of the coordinates in the hinge point. Assuming that the deformations of the plate are small enough to allow neglecting of the second and higher powers of (dy/dx) and introducing the quantities

$$\ell_1 = \sqrt[4]{m^2ET^3/12(m^2-1)\theta_1 g} \quad \ldots\ldots (52)$$

and

$$D_0 = 2\theta_1 g \ell_1^2 \quad \ldots\ldots (53)$$

where θ_1 is the specific density of the substratum, we obtain differential equation (54) for the displacement y of the plate in the vertical sense.

$$\ell_1^4(d^4y/dx^4) + 2(D/D_0)\ell_1^2(d^2y/dx^2) + y = 0 \quad \ldots\ldots (54)$$

Here D is the force of compression per unit of length perpendicular to the XY plane. The quantity ℓ_1 has the dimensions of a length, and, introducing the quantities hitherto adopted, namely, θ_1 = 3.27, E = 1,000,000 kg/cm^2, and m = 4.1, we obtain for T = 30 km the value of ℓ_1 = 52 km.

Examining Equation (54) we find that for $D = D_0$ the solution is simple; y is then represented by a sine curve, and if we no longer neglect in this case the second and higher powers of (dy/dx), we see that for a slight increase of D the amplitudes quickly become greater. Obviously D_0 is the buckling limit for the Earth's crust if it has no break or hinge; if D exceeds this limit the amplitudes become so large that in one of the waves the crust will yield. For our investigation we shall assume $D \leq D_0$, and to simplify our deductions we shall introduce the angle β as in (55).

$$(D/D_0) = \cos 2\beta \quad \ldots\ldots (55)$$

We see that β can vary from 45° for D = 0 to 0° for $D = D_0$.

By substituting (55) in (54) we can derive the general solution as in (56A) for positive values of x; for negative x we find the same curve mirrored with regard to the Y axis. The origin in this solution in general is a discontinuity point. We assumed that the deformations disappear for x becoming infinite.

$$y = Ae^{-ax}\cos(bx + \varphi) \quad \ldots\ldots (56A)$$

where A and φ are integration constants and a and b are given by

$$a = (\sin\beta)/\ell_1 \qquad b = (\cos\beta)/\ell_1 \quad \ldots\ldots (56B)$$

By differentiating y with regard to x we find (56C) and (56D).

$$(dy/dx) = -(A/\ell_1)e^{-ax}\sin(bx + \varphi + \beta) \quad \ldots\ldots (56C)$$

$$(d^2y/dx^2) = -(A/\ell_1^2)e^{-ax}\cos(bx + \varphi + 2\beta) \quad \ldots\ldots (56D)$$

By integrating with regard to x, we obtain (56E) for the vertical force P_0, which has to work on the crust at the origin of coordinates to maintain the deformation as given by (56A).

$$P_0 = -2\theta g\int_0^\infty y\,dx = -2\theta g\ell_1 A\sin(\varphi - \beta) \quad \ldots\ldots (56E)$$

The length L of the waves represented by (56A) is given by (57).

$$L = (2\pi/b) = 2\pi\ell_1 \sec\beta \quad \ldots\ldots (57)$$

So we have for D = 0 a wave length L = 8.90ℓ_1 and for $D = D_0$ a wave length L = 6.28ℓ_1.

Applying these formulas to our problem, we can derive the integration constant φ from the condition that at the hinge point, that is, at the origin of the coordinates no force is working on the crust and so we have $P_0 = 0$ or

$$\varphi = \beta \quad \ldots\ldots (58)$$

A second condition is provided by the presence at this point of a hinge, which implies that the momentum of stresses M in the cross-section through the origin is zero. As the momentum M is proportional to (d^{2}y/dx^2) this condition gives (d^{2}y/dx^2) = 0 for x = 0. By using (58) we obtain $(A/\ell_1^2)\cos 3\beta = 0$. This condition leaves two possibilities:

$$A = 0 \quad \ldots\ldots (59A)$$

or

$$\beta = 30° \quad \text{(59B)}$$

This means that the constant A must be zero as long as the compressive force D is smaller than the value corresponding to (59B), or, in other words, that in this case no deformation occurs. If D reaches this limit, however, all values of A are possible, that is, large deformations can originate. Obviously this value of D represents the buckling limit of the crust in this case. Indicating it by the index 1 and deriving its value from (55) in connection with (59B), we obtain (60).

$$D_1 = (1/2)D_0 \quad \text{(60)}$$

By means of (52) and (53) we can express this value in the original data of our problem. Formula (60) gives us the important conclusion that the presence of a hinge line reduces the buckling limit of the crust to one-half of the value for the unbroken crust.

It is interesting to derive the deformation for this case. Introducing $\varphi = \beta = 30°$ in (56A) we obtain

$$\begin{aligned} y &= Ae^{-x/2\ell_1} \cos[0.866(x/\ell_1) + 30]° \\ &= Ae^{-x/2\ell_1} \cos[49.62(x/\ell_1) + 30]° \quad \text{(61A)} \end{aligned}$$

According, then, to (57), the wave length is

$$L_1 = 380 \text{ km} \quad \text{(61B)}$$

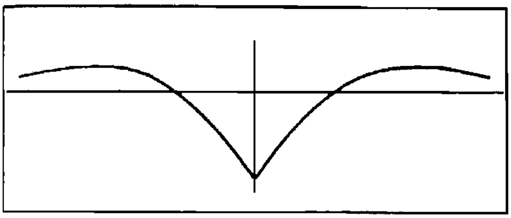


Fig. 26--Deformation due to buckling

Studying this deformation we see that the waves of buckling in this case die out quickly on both sides of the hinge point (see Fig. 26). So, if our assumption that a shear plane in the crust acts as a perfect hinge, the buckling force would be reduced to one-half of the normal value.

This assumption will no doubt not represent the real circumstances in the Earth's crust. The thickness of the crust must bring about resistance to bending, even if the crust is intersected by a fault plane, but it must remain true that in this case the resistance is less than normal. It is difficult, however, to estimate the amount of lessening of the resistance, and so an exact treatment of the problem is hardly possible. We can say that in this case (d^2y/dx^2) does not disappear in the fault plane of the crust, that is, at the origin of the coordinates, but that we can probably obtain an approximation to the real conditions by assuming it to be proportional to the change of (dy/dx) in this area or, what amounts to the same thing, to the value of (dy/dx) for $x = 0$. Pursuing this way of solution, we find that thus the value of β for buckling must be smaller than 30° and that D is a larger fraction of D_0 than what we have found above; if the resistance to bending assumed at the origin tends to the normal value, β tends to 0° and D to D_0. We may conclude that as a shear plane in the crust is certain to diminish the resistance, the buckling force must be correspondingly smaller, but the amount of this decrease is difficult to derive.

This decrease of the buckling force, due to the presence of a crustal fault plane, must obviously cause the orogeny to follow this plane by preference, even if the compressive force is not perpendicular to it. Only if the deviation from the perpendicular direction is large can we expect folding to originate in an independent direction.

The above reasoning is further strengthened by the consideration that a large part of the crustal deformation in the orogenic belt must have a plastic character, and that the plastic flow which we have assumed to take place in the zones of crustal shear is likely thus to facilitate the coming into being of the tectonic deformation. This, therefore, is a second reason--and perhaps even a stronger one than the first--to expect that the orogeny will follow by preference the fault zones of the crust.

We have hitherto considered only the course we may expect the zone of strong crustal shortening to take. There can be no doubt, however, that, besides, a certain number of shear planes will become active again through the differential movements the crustal blocks must undergo. In many cases these shearing movements must also give rise to topographic features: (a) It may bring about renewed volcanism in these lines, (b) The roughness and the irregularities of the planes may cause material to be squeezed out during the relative movement of the two blocks on both sides of the plane; (c) A deviation from parallelism of neighboring planes, by the movement of the crustal block between in the sense of their converging, may give rise to compression of this block. Such a deviation as (c) may be present if the fault planes in the crust do not quite follow the directions of our Net, but even if they do, the planes are in general not exactly parallel; from Figure 7 we can derive that, to undergo compression, the block movement has then to occur in a direction away from the horizontal or vertical axis of this Figure. In our Net in Mercator projection these axes are found in the curves through the points of maximum stress on the equator; these points are marked by the indication 1.00. In the final case--probably more important than the two preceding ways in which topography may be imagined to originate--we may expect the coming into being of topography over shear planes, in which renewed movement occurs, if the orogenic force working on the crust has a component at right angles to the shear line. If the plane has a tilt with regard to the vertical this component must cause relative movements of the crustal blocks in a vertical sense, and, if the component is somewhat larger, we may perhaps even expect folding, although this must be slighter than in the main tectonic belt. We may probably find a good example of such a phenomenon in the crustal belt along the west coast of Sumatra, where evidence of folding has been obtained on some of the islands, while the gravity profiles over this belt seem to indicate a riding of the Sumatra block over the oceanic block. The crustal movements accompanying earthquakes in Sumatra nearly always occur along fault planes parallel to the belt; this confirms the conclusion that the principal part of the movement took place in this direction, that is, in the direction of the shear plane.

The fact that the topography in an orogenic belt may originate in numerous other shear lines besides the main zone of compression may give a simple explanation of at least part of the complicated pattern of the mountain formations known for most of the geosynclines on Earth. We may apply this to the alpine orogeny where the strike of the Dinarides, the Apennines, and the southeast-northwest part of the Carpathians might be explained by the pre-existing fault planes in the southeast-northwest direction of our Net, while fault planes in the other direction of the Net may well have played a part in the origin of parts of the other ranges, for example, in the course of the western parts of the Alps and of the Carpathians. From the amount of the compression in the different ranges we may derive that the general direction of the compression must probably have been south-southeast to north-northwest, although local deviations may possibly have occurred, and that it is likely that the crustal blocks of the Adriatic Sea and of Italy have had the greatest relative displacement with regard to the blocks north of the Alps. A more intensive study is required to make sure about these suppositions and to obtain further insight into these problems, but without doubt we may already state that the conception of a subcrustal current exerting its force on a system of separate crustal blocks with fault planes between, promises a better understanding of the intricate alpine orogeny than the hypothesis that forces have worked on an unbroken crust. In this last case it is difficult to explain the presence of the irregular field of forces needed to produce this pattern.

Southern Asia is another area where our hypothesis can give a better understanding of the trends of the Cenozoic orogeny; we may suppose that the mountain ranges of Baluchistan and Burma are connected with the corresponding directions of our Net which are also represented in the map of the main shear zones of the Earth in Figure 10, whereas the Himalayan Ranges must entirely have been brought about by the compressive forces. Here again the assumption of pre-existing fault zones in the crust helps to understand the pattern of the orogeny.

A further instance is provided by the East Indies and the Philippine Islands. As already mentioned, the gravity field as well as the topography show correlation with our Net and the part played by a few of the great shear zones, such as those along the west coast of Sumatra and the east coast of the Philippine Islands can explain the great arc formed by the orogeny. This is welcome, because the gravity anomalies point strongly to a single direction of the movement of the crustal blocks inside the great arc, namely, to the south-southeast, and not to a movement from the center towards the periphery, and so the origin of much of the orogeny, for example, that along the west coast of Sumatra where its direction makes only a small angle with the direction of the compression, is difficult to understand without the assumption of pre-existing fault planes in the crust.

We shall not here pursue this subject further. A more thorough investigation is needed as well as a detailed geological study in order to do justice to the difficult and many-sided problems involved in all these areas--something that can not be undertaken in the present paper.

A last cause leading to correlation of topography with the Net of shear planes in the crust is the way in which erosion is affected by the presence of shear planes. As these effects are clear, we shall not go deeply into this question here; SONDER'S paper [1938, p. 214 ff] gives a valuable discussion of it. He points out how the presence and "working" of the crustal fault planes must strongly affect the action of the erosion; this must bring about an orientation of the rivers and water courses in these directions. Figure 19 shows an example published by Hobbs; many others may be found in the papers of the lineament tectonicians mentioned in Chapter III. Sonder further deals with the effect of the fault planes on glacial erosion, which must likewise be strongly affected by it. Many examples are given by these same publications, of which three are represented in Figures 16, 17, and 20.

Our survey of the ways in which the origin and the presence of a system of shear planes can lead to a correlated topography is thus completed. The most difficult problem of all remains to be discussed, that is, the question of how we can explain the correlation of the continental coasts with our Net. We have seen in Chapter III that this correlation seems to be present although it is smaller than that of the topography as a whole. In attacking this question we are handicapped by the fact that the origin of continents and oceans is still an unsolved problem. On the other hand, we may thus hope that the solution of our present problem may shed light on this greater one.

Examining our problem more closely, we see that the correlation of the continental coast lines with our Net, or rather of the edges of the continental shelves, raises the difficulty involved in that the course of these shelf edges must be later than the shearing catastrophe of the crust and, therefore, later than the origin of a rigid crust of some thickness, whereas the geological, seismological, and gravimetrical data indicate strongly that the sialic layer is thinner for the oceans than for the continents and even is absent in a great part of the Pacific and, possibly, of the Arctic Ocean. We thus are confronted by the question of how it is possible that the course of the borders of these structural differences can have originated after the formation of the rigid crust. The gravimetric profiles observed at sea at about right angles to the continental coasts point in general indeed to the coincidence of these borders with the edges of the continental shelves.

Before trying to find an answer to this question, we may remark that the above-stated fact excludes the hypothesis that the continental sialic blocks originally formed a whole, and that a disruption of this mass, occurring in a period in which the basaltic layer was still plastic, gave rise to the formation of separate parts drifting away from each other and forming the continental blocks of today. A few authors, Osmond Fisher and others and recently B. G. Escher, have made this hypothesis in connection with the idea that at the moment the Moon broke away from the Earth a great part of the sialic mantle was carried off, while the remaining part broke into the separate blocks mentioned. The hypothesis, however, that at least the greatest part of the blocks thus formed had the contours of the present continents, is not compatible with our statement that these contours must have been formed after the formation of an entire rigid crust over the Earth.

Taking up our problem as to how this can have happened, the writer sees two possibilities; (a) that the formation of the continental sial blocks was as a whole later than that of the rigid crust and of the shearing catastrophe, and (b) that only their outline was formed later. For the first solution it seems that only one hypothesis is at present available, namely, that of RITTMANN [1939], but as this offers serious difficulties--as Umbgrove stated to the writer in a private letter, it is hard to understand the enormous sedimentation in the primitive oceans which, according to Rittman, must have led to the formation of the granite of the continents--we shall not discuss it further. The second possible assumption supposes that the greatest part, if not all, of the present continental contours has been formed by a tectonic folding orogeny, thus enlarging the sial continents by new zones of sialic material. As we have seen in the preceding pages that orogenic zones have a preference for following the trends of the fault planes in the crust, the correlation of the continental shelf edges with the Net of shear planes could thus be understood. The important question to answer is whether our assumption can be admitted with regard to our knowledge of the geology of the continental edges.

It is clear that this does not present any difficulty for all the coasts and shelf edges bordered by recent orogeny, such as the west coast of North and South America and the east coast of Asia. Where this orogeny is parallel to the coast we may admit at once that the direction of the shelf edge is determined by the trend of the orogeny. But even where the geology provides indications that the orogeny is cut off by the coast and sunk away, as, for example, to the northwest of Payta in northern Peru [STEINMAN, 1929; see also p. 52 of the present paper], a correlation of the coast line with the directions of our Net may obviously be expected also; it is clear that the presence of fault planes in the crust must favor the shear taking place along one of these planes. These mountain coasts can not in themselves, however, explain the percentage of the correlation found for all the coasts together. In Chapter III we have found that the percentage of the correlation for the mountain coasts apart is of the same order as that found for all the coasts, and so at least a great part of the other coasts must also somehow be connected with the Net of shear planes.

The question thus presents itself whether also for these coasts we may suppose that they have been formed by orogeny. In this case the tectonic activity of course must have occurred in one of the early orogenic periods before the Cambrian. From the radioactive determinations of age given by HOLMES [1937] and NIER [1938-39], KUENEN [1941] concludes that against three orogenic periods since the beginning of the Cambrian eight periods occurred in the preceding ages up to 1800 million years ago, and possibly still more have taken place before that date. So there have been many periods before the Cambrian in which unknown orogeny has occurred, and there is no reason to reject the idea that the other shelf edges may thus have been brought about in one of these periods. As we know that orogeny in successive periods has often shifted towards neighboring areas, we may perhaps see in the old Palaeozoic folding of the Brazilides running parallel to the shelf edge of the east coast of South America over a great part of Brazil to Uruguay, a slight indication in favor of an old folding determining the trend of this shelf edge. For the east coast of Africa such an indication might perhaps be found in the presence of the neighboring Carlsberg Ridge and Seychelles Bank, which by their curved form and the sial on their islands seem likely to be of orogenic origin. For the most northern part of the northwest coast of Africa an orogenic origin is known and so here the possibility of a correlation with our shear Net is evident. Concluding we may say that an orogenic origin of many, if not all, of the continental shelf edges seems possible.

We shall now consider our supposition in connection with two recently advanced theories about the origin of continents. In the first place we may mention UMBGROVE'S hypothesis [1942, pp. 104 ff], according to which the sial layer originally covered the whole Earth in about equal thickness and afterwards was thrust together in continental blocks by subcrustal currents. On this supposition he explains the three predominant levels of the topography at the Earth's surface pointed out by him, that is, (a) the depth of a great part of the Pacific and probably the Arctic Ocean where the sial is entirely absent, (b) the somewhat lesser depth of the Atlantic and Indian Oceans where probably a thin sial layer is present, and (c) the continental parts where the sial has been so much compressed that the blocks after subsidence in isostatic equilibrium rose above sea level. We can not assume that the sial in the Atlantic and Indian Oceans is the undisturbed original layer, for the compression of this layer in a measure corresponding to the area of the parts where the sial is lacking is insufficient to account for the sial blocks of the continents; we must, therefore, suppose that the layer in these oceans has been stretched by subcrustal currents or other causes or that the original layer had already thicker parts in those areas where the continents were formed afterwards.

Umbgrove assumes that the main compression leading to the growth of the continents has taken place at a time when the crust had not yet been entirely solidified. There is every reason to suppose, however, that the subcrustal currents have continued in later times and caused the periods of tectonic orogeny, and so our supposition that at least part of the continental edges have been formed in these later periods fits well with Umbgrove's hypothesis. One remark, however, must be made. If we accept the general view that the subcrustal currents producing the tectonic phenomena were caused by convection--a supposition forming also the basis of the explanation by GRIGGS [1939] of the periodicity of these phenomena--we must expect a higher temperature in the continental sial blocks with regard to the neighboring ocean crust because of the higher percentage of radioactive material of the sial and of the difference in the surface conditions, and this must have brought about rising convection currents below the continents and flown outwards below the continental edges. So these later currents must have had an opposite direction to those which, according to Umbgrove, in the first phase of the Earth's history caused the thrusting together of the sial blocks.

The second hypothesis about the formation of the continents has been advanced by the writer for the purpose of accounting for the curious systematic distribution of the continents on the Earth's surface. It has been noticed long ago that in general the continents have oceanic areas at their antipodes, for example, North America, the Indian Ocean, Australia, the North Atlantic, Antarctica, the Arctic Ocean, etc.; only five per cent of the continental areas form an exception to this law. It further strikes us that the distribution has somewhat the character of a tetrahedon, the four corners being represented by the Siberian Shield, the Canadian Shield, the Scandinavian Shield, and the Antarctic Continent, the continents having more or less a triangular shape pointing southward and their bases forming a ring in the north which finds its counterpart in the ring of water around the Antarctic Continent [STEERS, 1932; UMBGROVE, 1942, pp. 81 ff]. As is well known, Lowthian Green has tried to explain these peculiarities by the hypothesis that because of contraction the Earth tries to assume the shape of a tetrahedon, and De Lapparent, Gregory, Arldt, Dacqué, and Kober later supported this or similar theories. The theoretical basis is hardly acceptable, however, and a still stronger objection may be found in the fact that the geoid does not show any perceptible bulges in the corners of a tetrahedon; the sial crust is in isostatic equilibrium, and so the elevations are not caused by an outward bending of the crust but by its being thicker in those parts. The hypothesis, therefore, no longer finds support.

The writer has proposed [VENING MEINESZ, 1944] another explanation which seems to him to be more tenable. It starts from the assumption that the formation of the continents has been connected with the system of convection currents which we may suppose to have been present in the Earth during its first cooling phase. JEFFREYS [1929] supposes that at that time the nickel-iron core had already been formed and on that basis we may suppose that the currents took place in the mantle of 2900 km outside this core. By means of a solution for convection currents in the sphere on the same lines as LORD RAYLEIGH'S [1916] solution for a plane layer, we can show that a system of four rising currents and four descending currents, each of them covering an octant, is the most probable under these conditions. Antipodal to each rising octant is a descending one, and the centers of the four rising octants form the corners of a tetrahedon as well as those of the descending octants. So we see that, admitting the connection with the formation of the continents, the above-mentioned peculiarities in the distribution may be explained.

Kuhn and Rittmann have expressed serious doubts that the nickel-iron core of the Earth could have differentiated during the time elapsed since the beginning of the Earth's history, and they certainly can not accept the possibility of its having done so in the relatively short time estimated for this event by Jeffreys. If we admit the validity of their arguments, we come to another picture of what has happened. We then must suppose that the octant system of convection currents has originated for some reason or other, perhaps because of its being the only perfectly regular distribution of areas of more-or-less equal dimensions in all senses, over the Earth's surface where in every corner point an even number of areas come together, while for our system of currents such a number is obviously necessary because otherwise two areas of the same kind--rising or descending--would be adjoining each other. Once having admitted the formation of this system of currents, it follows from the above-mentioned equations for convection currents that they must have extended to a depth of about 2900 km and below this depth the solar material, rich in hydrogen, according to the views of Kuhn and Rittmann, would have remained unchanged; it forms the heavy core of the Earth, and the abnormal properties of the core revealed by seismology seem to be in accordance with this idea. The currents in the mantle could explain that differentiation has extended down over its whole depth to the core.

Examining the connection of the system of convection currents with the formation of the continents, it is clear that it is easy to bring it into harmony with Umbgrove's hypothesis; the currents provide the cause for the thrusting together of the sial layer supposed by Umbgrove to have led to the forming of the continental blocks. These blocks must then be assumed to have originated above the descending currents. We thus arrive at a satisfactory incorporation of the explanation of the tetrahedral distribution in this hypothesis. Two points, however, deserve our attention. In the first place we may presume that the concentration of sial, which is rich in radioactive matter, above the descending column must in the long run have brought about a rise of temperature with regard to the areas above the rising column, and so it seems doubtful whether the currents could have continued to flow in the same sense. As a change of the direction of flow would have destroyed the sial concentrations at the surface we must suppose that, before such a change could have occurred, the solidification of the crust prevented this from taking place. This is in harmony with Umbgrove's view that the continental sial blocks must have been formed before the crust as a whole had solidified. A second more difficult point is the problem of understanding how the rising current below the Atlantic and the Indian Oceans could have brought about a stretching of the original sial layer without taking it away entirely.

We can also suppose another connection between the formation of the continents and the system of convection currents which has the advantage that change in direction of flow need be assumed; it is based on the following hypothesis regarding the origin of the continental sial blocks. Assuming that the currents have formed before the sial layer, we shall suppose that the sial was brought to the surface by these currents and that the temperature there was such that the solidification of the crustal layer prevented the flowing out of the sial in a continuous layer over the Earth, or that at least the viscosity was high enough to prevent this. We may in this case expect the forming of the continental sial blocks above the rising currents. The thinner layer below the Atlantic and Indian Oceans could have originated in the beginning when the cooling was less and the flowing out still possible over part of the Earth's surface. The gradual rise of temperature to be expected in the continental blocks with regard to neighboring areas, because of the greater amount of radioactive material in the sial, would tend to stabilize the system of currents.

We shall not enter here into a more detailed discussion of this hypothesis, but we may remark that like Umbgrove's it may be brought in harmony with our supposition about the origin of the continental edges. Here again we must consider it likely that the currents have continued to occur in the later periods of tectonic orogeny, and that many of these edges have been formed by the thrusting together of the sial crust by these currents. For this hypothesis these later currents can be supposed to have flowed in the same direction as the original ones, for in both cases the direction must have been away from the continent.

We may conclude that for Umbgrove's hypothesis, as well as for that of the writer, the formation of continental edges correlated with the shear pattern could be explained.

References

AHNERT, E., Morphologische und geotektonische Skizze des russischen fernen Ostens etc., Proc. Third Pan-Pacific Cong., Tokyo, v. 1, pp. 491-533, 1926.
BÖNECKE, G., Veröff. Inst. Meeresk., A, Heft 32, 1936.
BORN, A., Der geologische Aufbau der Erde: Tiefenkarte des Mittel und Südatlantik, nach DEFANT, Meteor Expedition, Handb. Geophysik, v. 2, pt. 2.
BROWN, T. T., and HESS, H. H., The Navy-Princeton Gravity Expedition to the West Indies in 1932, Govt. Print. Off., Washington, 1933.
BUCHER, WALTER H., The deformations of the Earth's crust, Princeton, 1933.
BULLARD, E. C., Gravity measurements in East Africa, Phil. Trans., R. Soc., v. 235A, no. 756, pp. 445-531, 1936.
BYERLY, PERRY, Comment in LAWSON, ANDREW C., The Sierra Nevada in the light of isostasy, Bull. Geol. Soc. Amer., v. 48, pp. 2025-2031, 1938.
BYLAARD, P. P., Beschouwingen over de knikzekerheid en de plastische vervormingen van de aardkorst in verband met de geologie van den O. I. Archipel, Ingr. v. Ned. Indie, v. 11, 135 ff, 1935.
BYLAARD, P. P., Théorie des déformations plastiques et locales par rapport aux anomalies négatives de la gravitation, aux fosses océaniques, aux géosynclinaux, au volcanisme, à l'orogénie et à la géologie de l'océan Pacifique occidental, Union Géod. Géophys. Internat., Assoc. Géod., Rapport de la Conférence d'Edinbourg, 1936.
BYLAARD, P. P., De Ingenieur, no. 37, 1931, and no. 23, 1933; De Ingenieur in Ned. Indie, no. 11, 1935, and no. 8, 1939.
COMMITTEE ON THE MEASUREMENT OF GEOLOGIC TIME, Report of, pp. 76-81, 1938-39.
COSTER, H. P., The gravity field of the central and western Mediterranean, J. B. Wolters, Groningen, 1945.
DAUBRÉE, A., Synthetische Studien zur Experimentalgeologie, Braunschweig, 1880.
DEFANT, A., Die Altair Kuppe, in: Bericht über die ozeanographischen Untersuchungen im zentralen und östlichen Teil des Nordatlantischen Ozeans in 1938, Berlin, 1939.
GRIGGS, DAVID, A theory of mountain building, Amer. J. Sci., v. 237, no. 9, pp. 611-650, 1939.
GUTENBERG, B., The internal constitution of the Earth: Ch. 7, The elastic constants of the interior of the Earth, McGraw-Hill, New York and London, 1939.
HELMERT, F. R., Die mathematischen und physikalischen Theorieen der höheren Geodäsie, Leipzig, B. G. Teubner, v. 2, pp. 426 ff, 1884.
HENCKY, H., Zur Theorie plastischer Deformationen, Proc. First Internat. Cong. App. Mech., pp. 312 ff, 1924.
HESS, H. H., Gravity anomalies and island arc structure with particular reference to the West Indies (anomaly map and bathymetric chart), Proc. Amer. Phil. Soc., v. 79, no. 1, 1938.
HOBBS, W. H., Repeating patterns in the relief and the structure of the land, Bull. Geol. Soc. Amer., v. 22, pp. 123 ff, 1911.
HOBBS-RUSKA, Erdbeben, Leipzig, 1910.
HOLMES, ARTHUR, The age of the Earth, Nelson Classics, 1937.
HUBER, M. T., Die specifische Formänderungsarbeit als Mass der Anstrengung, Czasopismo Techniczne, Lwow, 1904.
JEFFREYS, H., The Earth, pp. 138 ff, 1929.
KENNEDY, W. Q., and ANDERSON, E. M., Crustal layers and the origin of magmas, Bull. Volcan., ser. 2, v. 3, p. 34, 1938.
KRENKEL, E., Die Bruchzonen Ostafricas, Berlin, 1922.
KRENKEL, E., Geologie Africas, Berlin, 1925.
KUENEN, PH. H., The negative isostatic anomalies in the East Indies, Leidsche Geol. Med., v. 8, no. 2, pp. 169-214, 1936.
KUENEN, PH. H., Major geological cycles, Proc. Ned. Akad. Wet., v. 44, no. 3, 1941.
KUIPER, H., Poolbewegingen tengevolge van poolvluchtkracht, N. Holl. Uitg. My., p. 80, Amsterdam, 1943.
LAMBERT, W. D., The interpretation of apparent changes in mean latitude and the International Latitude Stations, Astron. J., v. 34, p. 904, 1922.
MILANKOVITCH, Astronomische Mittel zur Erforschung der erdgeschichtlichen Klimate, Handb. Geophysik, v. 9, pt. 3, 1938.
NIER, see Comm. Measurement of Geol. Time, 1938-39.

RAYLEIGH, LORD, On convection currents in a horizontal layer of fluid, when the higher temperature is on the under side, Phil. Mag., v. 32, pp. 529-546, 1916.
RITTMANN, A., Über die Herkunft der vulkanischen Energie und die Entstehung des Sials, Geol. Rundschau, v. 30, nos. 1 and 2, pp. 52-60, 1939.
RUSSELL, R. J., Morphologie des Mississippi deltas, Geogr. Zs., v. 45, no. 8, 1939.
SAURAMO, Soc. Geol. Finl., v. 13, 1939.
SEDERHOLM, J. J., Weitere Mitteilungen über Bruchspalten und Geomorphologie, Bull. Comm. Géol. Finl., p. 37, 1913.
SONDER, R. A., Grosstektonische Probleme des mittelamerikanischen Raumes, Zs. Vulkanologie, v. 17, p. 1, 1936 and 1938.
SONDER, R. A., Eclogae Helvetiae, Fig. 1, 1938.
SONDER, R. A., Die Lineamenttektonik und ihre Probleme, Eclog. Geol. Helv., v. 31, pp. 199-238, 1938.
STEERS, J. A., The unstable Earth, Methuen, London, pp. 1 ff, 1932.
STEINMANN, G., Geologie von Peru, Heidelberg, 1929.
STOCKS, TH., Die Tiefenverhältnisse des Golfes von Aden, Zs. Ges. Erdk., pts. 5 and 6, 1941. [The reproduction is from copy in Geol. Rundschau, v. 33, p. 355, pts. 4 and 6, 1942.]
TABER, S., Fault troughs, J. Geol., v. 35, pp. 557-606, 1927.
UMBGROVE, J. H. F., The pulse of the Earth, p. 154, M. Nyhoff, The Hague, 1942.
VAN ITERSON, F. K. TH., Bydrage tot de plasticiteitstheorie, Versl. Ned. Akad. Wet., v. 52, no. 1, 1943.
VENING MEINESZ, F. A., Observations de pendule dans les Pays Bas, 1913-1921, Pub. Neth. Geod. Comm., Waltman, Delft, 1923.
VENING MEINESZ, F. A., Maritime gravity survey in the Netherlands East Indies: Tentative interpretation of the provisional results, Proc. Ned. Akad. Wet., v. 33, no. 6, p. 570, 1930.
VENING MEINESZ, F. A., Gravity expeditions at sea, Pub. Neth. Geod. Comm., Waltman, Delft, v. 2, pp. 109 ff and pp. 117 ff, 1934.
VENING MEINESZ, F. A., Tables fondamentales pour la réduction isostatique régionale, Bull. Géod., no. 63, 1939.
VENING MEINESZ, F. A., The Earth's crust deformation in the East Indies, Proc. Ned. Akad. Wet., v. 43, no. 3, 1940.
VENING MEINESZ, F. A., Tables for regional and local isostatic reduction (Airy system) for gravity values, Neth. Geod. Comm., Delft, Waltman, 1941 a.
VENING MEINESZ, F. A., Gravity over the Hawaiian Archipelago and over the Madeira area: Conclusions about the Earth's crust, Proc. Ned. Akad. Wet., v. 44, no. 1, 1941 b.
VENING MEINESZ, F. A., Topography and gravity in the North Atlantic, Proc. Ned. Akad. Wet., v. 45, no. 2, p. 120, 1942.
VENING MEINESZ, F. A., Die verdeeling van continenten en oceanen over het aardoppervlak, Proc. Ned Akad. Wet., v. 53, no. 4, 1944.
VENING MEINESZ, F. A.; UMBGROVE, J. H. F.; and KUENEN, PH. H., Gravity expeditions at sea, Pub. Neth. Geod. Comm., v. 2, pp. 140 ff, Waltman, Delft, 1934.
VENING MEINESZ, F. A., and WRIGHT, F. E., The gravity measuring cruise of the U. S. Submarine S-21, Pub. U. S. Naval Obs., 2nd ser., v. 13, app. 1, 1930.
VISSER, S. W., Spanningen in de aardkorst tengevolge van poolverschuivingen en het aardmagnetische veld, Versl. Ned. Akad. Wet., v. 52, no. 8, 1943.
WANACH, B., Eine fortschreitende Lagenänderung der Erdachse, Zs. Geophysik, v. 3, p. 102, 1927.
WINDHAUSEN, A., The problem of the cretaceous-tertiary boundary in South America and the stratigraphic position of the San Jorge formation, Amer. J. Sci., v. 44, fig. 3, p. 33, 1918.
WISEMAN, J. H. D., Basalts from the Carlsberg Ridge, in The John Murray Expedition, v. 3, no. 1.
WÜST, G., Das submarine Relief bei den Azoren, in Bericht über die ozeanographischen Untersuchungen im zentralen und östlichen Teil des Nordatlantischen Ozeans in 1938, Berlin, 1939.

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