Pentti Kaitera

Mechanism behind sea-floor spreading

Appendix: H. Kutvonen. Calculating movements and stresses in the earth's crust using a two-dimensional, high viscosity fluid flow model

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MECHANISM BEHIND SEA-FLOOR SPREADING

Pentti Kaitera

CALCULATING MOVEMENTS AND STRESSES IN THE EARTH'S CRUST USING A TWO-DIMENSIONAL, HIGH VISCOSITY FLUID FLOW MODEL

H. Kutvonen

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MECHANISM BEHIND SEA-FLOOR SPREADING

by

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Abstract

The author has developed a hypothesis, known as the sea-pressure hypothesis [13, 14, 15], for explaining the mechanism behind the large horizontal movements of the Earth's crust, and he has applied this hypothesis to the research findings of sea-floor spreading. By sea-pressure he means the difference in stresses of the upper mantle material between the ocean and continent under the influence of erosion and sedimentation and the increase in sea volume during geological time as well as the pressure against the continental coasts when the sea-floor is moving towards them.

To supplement this hypothesis, the article suggests that the temperature difference in the upper mantle between the continent and ocean causes the altitude difference in the easily-flowing layer in the asthenosphere. For this reason the loading against this layer is greater in a sea area than in a continental area. This pressure difference can be observed near the trenches where the gravity anomalies are developed due to such high velocity of the flowing mantle material that the isostasy forces have not been capable of levelling them. The trenches show the places of mass deficit, and the surplus of mass has been collected immediately beside the trenches in the direction of the material flow. Gravity measurements show that the pressure difference between the sea and continent can be as much as 300—1 200 kg/cm^2.

Such pressure differences can cause horizontal velocities in the sea-floor movement which are of the same order of magnitude as the speeds according to the sea-floor spreading hypothesis. The sea-pressure hypothesis can explain many geological and geophysical problems which have remained unsolved in spite of great efforts during this century. As well as the large sea-floor movements, continental drift, the building of the mountain ranges, the formation of the continental slopes and sea canyons, the generation of the central rifts, the great waves of the geoid h ghs, etc. can also be naturally interpreted. About 13.5 km^3 of the substance of the crust is annually transferred due to erosion from the continents into the seas. The formation of the new crustal material in connection with sea-floor spreading is of nearly the same order of magnitude. Without erosion and sedimentation the processes in connection with sea-floor spreading should have stabilized at a certain equilibrium between sea pressure and isostatic forces at an early stage of the Earth's history. Thus, erosion and sedimentation also have great influence on sea-floor spreading.

During the last 15 years understanding of the present stage and recent history of the ocean basins has increased enormously thanks to the resources spent on marine geology research. Especially in North America and Great Britain investigations have been made on the movements of the sea-floor, and as a result a new hypothesis has been developed known as the sea-floor spreading hypothesis. BULLARD describes the main results of these researches in his paper on the origin of the oceans [2], and MENARD [21] and EMERY [5] complete his description in the same issue of »*Scientific American*».

BULLARD comments that we are now in the middle of a rejuvenating process in geology comparable to that experienced in physics in the 1890's and to that now in progress in molecular biology. He writes further that we have enough examples of the magnetic messages concerning the reversal of the magnetic field of sea-floor rocks to leave no doubt about what is happening. The sequence of reversals and the progress of spreading is recorded in all oceans by magnetization of the rocks of the ocean floor. The only adjustable factor in the calculation is the rate of spreadir g. Such worldwide theoretical ideas and such detailed agreement between calculation and theory are rare in geology, where theories are usually qualitative, local and of little predictive value. Fig. 1 shows the research findir gs on these messages according to BULLARD; the oceanic rift system and the rate of sea-floor spreading in millions of years on both sides of the central rifts.

BULLARD mentions, however, that the history of the oceans does not

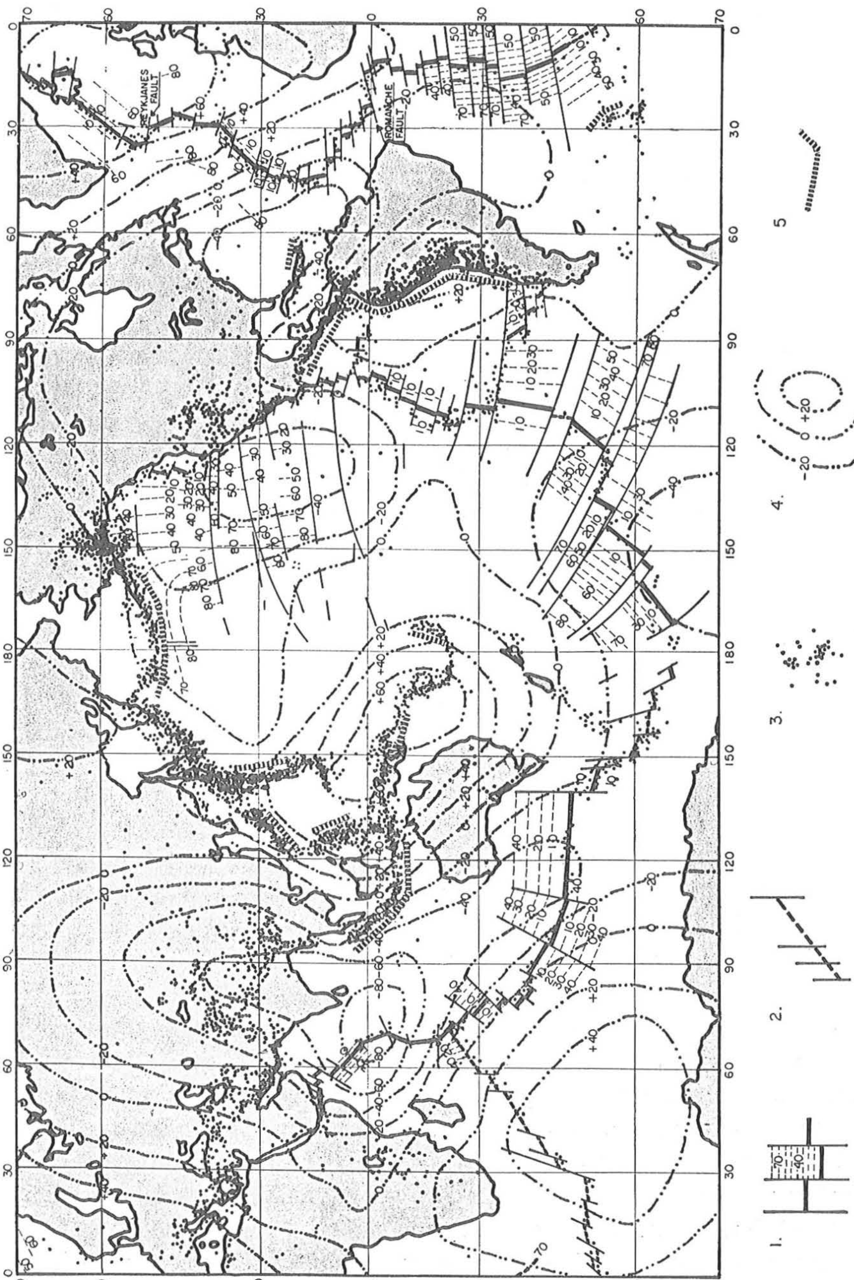

Fig. 1. Location of the central rifts according to BULLARD [2] and geoid highs (m) according to KAULA [16]. 1. Central rifts and fracture zones; the numbers show the age of the sea-floor in millions of years. 2. Estimated central rifts. 3. Location of the foci of earthquakes. 4. Plus- and minus-anomalies. 5. Trenches.

require an account of the mechanism behind the observed phenomena, and no very satisfactory account can be given. He refers to the traditional view that mantle behaves as a liquid when it is subjected to small forces for long periods, and that differences in temperature under oceans and continents suffice to produce convection cells in the mantle with rising currents under the mid-ocean ridges and sinking ones under the continents. These hypothetical cells would carry the plates along like a conveyor belt and provide the forces needed to produce a split along the ridge. BULLARD thinks this view may be correct, but on the other hand he remarks that the theory is implausible in that convection does not normally happen along lines broken by frequent offsetts, as the ridge is. He also mentions other difficulties in the convection current hypothesis.

Discussion concerning the forces which are causing large horizontal movements of the crust has for about a hundred years been the central unsolved problem in geology. There are many and varying theories for the solution of this problem. They were first developed in connection with orogenesis and later also in connection with continental drift. SCHEIDEGGER [26] mentions that it is necessary to re-examine *all* theories of orogenesis that have ever been invented in order to determine what can be saved from them in the light of the presently available facts. If this is done, it immediately becomes obvious that something fundamental is wrong with each and every one of the theories. The contraction and convection theories have many difficulties; in the continental drift theory the forces producing the shifts are a mystery; expansion theories could presumably produce only a few fissures here and there, and the same is also true of hypotheses basing orogenesis upon effects of the rotation of the Earth.

It is obvious that the same forces which are at work in orogenesis or continental drift are also operative in sea-floor spreading. At present, following research findings on sea-floor spreading, most of these theories have been abandoned due to the extent of these horizontal crustal movements. The convection current hypothesis, with different variations and supplements, seems to arouse attention, however. But the machanism of these currents is as yet unknown, and therefore there are difficulties in adapting them to the geological observations; mathematically, too, there are difficulties in finding the right model. For instance, when CHAMALAUN and ROBERTS [3] made their attempt to find such a model, MACDONALD [20] comments on these calculations that, even if the unrealistic physical model is accepted, the treatment considers only the onset of the instability. The numerical parameters used by CHAMALAUN and ROBERTS guarantee a priori a turbulent convection, so that the destruction by nonlinearities of the symmetric flow pattern eliminates the very purpose of the convective hypothesis, that of providing an organized dragging force on the base of the crust. TURCOTTE and OXBURG [28] have referred the last researches concerning this subject and developed new models. Their hypothesis seems to be one of the best attempt to estimate the possibilities of the convection currents in connection of the central rifts, but there are still many unsolved problems which have caused criticism [1, 2, 23].

The need to explain which forces are working behind sea-floor spreading has begun to arouse opposition to the whole hypothesis. BELOUSSOV [1] has collected a number of remarks against this hypothesis and in conclusion comments that not a single aspect of the ocean-floor spreading hypothesis can stand up to criticism, and it is based on a generalisation of certain data whose significance has been overestimated. Some of the most important details of his remarks are these:

He mentions that neither the relief nor the magnetic peculiarities of the lower zones of the slopes of the mid-ocean ridge can be obtained by a simple downward movement of the upper zones. Such a movement could not have led to a change in the amplitude of relief and dimensions of its elements. Factual material demonstrates that the correspondence between magnetic anomalies on the mid-ocean ridge and the geomagnetic time scale is far from definitely established. It has repeatedly been pointed out that the distribution of both sediments and magnetic anomalies can be brought into correspondence with the ocean-floor spreading hypothesis only if we assume that the spreading rate has changed many times and considerably. An important element in the hypothesis is the symmetry of magnetic anomalies on either side of the ridge axis. Unfortunately the amount of factual data that would permit estimating the degree of symmetry does not match the significance attached to this problem. The most complex movements of the axes of spreading are presumed in the northeastern corner of the Pacific Ocean, where it is assumed that there is a simultaneous spreading in different directions (eastwards and northwards) and, at the same time, a migration of the spreading axes in the same directions, to the east under the continent of North America and to the north under the Aleutian Trench and the Bering Sea.

However, the greatest combination of oddities is observed in the region of the Gulf of Alaska and the Aleutian Island Arc where the strips of magnetic anomalies exhibit a right-angle turn. In the Upper Cretaceous, spreading occurred from three axes (latitudinal, meridional and with southwest to northeast strike) forming a »fork» in the Gulf of Alaska. In the Paleogene, the latitudinal axis located to the south of the Aleutian Island Arc was displaced northwards, passing under the Aleutian Trench and the Aleutian Island Arc and disappearing under the Bering Sea. At the same time, the meridional axis was displaced eastwards, going under the continent of North America.

These are only some of the points which have been made against the sea-floor spreading hypothesis. Before discussion of these remarks it may be mentioned that I have also proposed a hypothesis, known as *the sea-pressure hypothesis*, as an interpretation of the mechanism of the horizontal crustal movements [13, 14, 15]. By sea-pressure I do not only mean the pressure of sea water but also the difference in stress produced between the ocean and continent under the influence of erosion and sedimentation and the increase of sea volume during geological time as well as the pressure against the continental coasts when the sea-floor is moving towards them.

The data presented in connection with the sea-floor spreading hypothesis on extensive and rapid movements of the sea floor led to a search for a greater difference in loading between oceanic and continental area than I had previously supposed. This was my reason for studying the question of the kinds of difference in loading prevailing at depths of 50—100 kilometres, where the upper limit of the asthenosphere may be located, because the flow of the mantle material due to the pressure difference begins in the layer where the viscosity is lowest. It seems obvious that the main flow of the material which is dragging the sea-floor horizontally should happen in this upper mantle layer.

The temperature of the Earth's crust below the continents at the sea-floor level is over a hundred degrees (°C) higher than on the sea-floor. Since the loss of heat from the sea-floor is on average of the same order of magnitude as from the continental surface, this difference does not disappear immediately. According to GUTENBERG [10] the heat flow is 1.2×10^{-6} cal/cm^2 sec for the whole Earth. Another reason for the temperature difference between the oceanic and continental upper mantle is the heat production due to radioactivity. According to JEFFREYS [10] the radioactive heat production in rock samples is on average as follows:

Rock type	Region	Heat cal/cm³year
Granitic	Greenland, Iceland, Scotland, Ireland, Japan	51
»	Finland and Alps	145, 149
Basaltic	Greenland, Iceland, Scotland, Ireland	39
»	England, Germany, France, Hungary	45
Plateau basalts		26
Island basalts		29
Dunites		17

These results show that the production of radioactive heat is greater in the granite-crust of the continental area than in the basaltic sea-floor. It is obvious that the temperature difference has still not levelled out at the continental Moho-surface; and also from here downwards at least to the upper part of the asthenosphere the mantle material in the continental area is warmer, and thus lighter, than at the same depth below the sea, although the difference in temperature has been reduced.

The viscosity of a similar substance is lower at higher than at lower temperatures. This means that the altitude of the easily-flowing layer is higher below the continent than below the sea. For this reason as well, then, the load on it is less in a continental area than a sea area. If we assume that the difference in altitude between the same temperature under continent and under ocean has decreased to, for example, 1—2 kilometres (at sea-floor level it is, in certain conditions, 4—6 km), such a difference does not emerge in seismic measurements as an indicator of differences in viscosity, as can be concluded according to Fig. 2 [24].

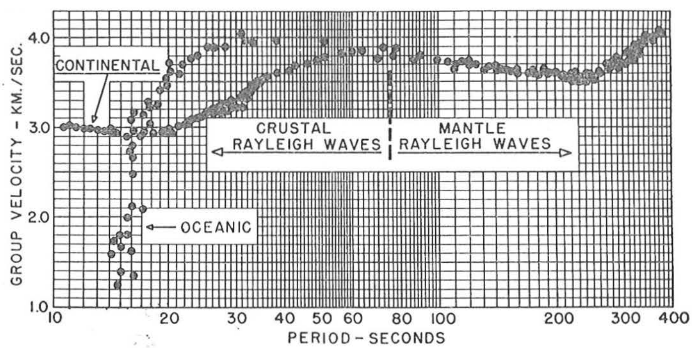

Fig. 2. Observed dispersion of *Rayleigh waves* in the period range 10 to 400 seconds after Ewing and Press [24].

On the basis of the above, the pressure at the easily-flowing layer of the mantle below the sea may be more than 340—680 kg/cm^2 greater than below the continental area (the density of the mantle material at this depth may be 3.4 g/cm^3). The magnitude of this assumption is not overestimated because the gravity anomalies near the trenches are from 120 to 500 milligal as can be seen from the following examples:

Trench	Gravity anomaly milligals			Remarks	References
	below the trench	behind the trench	difference[1])		
Japan Sea to Indian Ocean near Djakarta	−140	+ 70	210	Hayford-Pratt anomalies	GUTENBERG (10) after VENING MEINESZ
East of southern Honshu, Japan	−100	+110	210	Airy-Heiskanen anomalies	GUTENBERG (10) after HEISKANEN
Puerto Rico Trench	−340	+150	490	Computed free-air anomalies	HEEZEN (11) after TALWANI
Philippine Trench, Surigao Strait	−120	+180	300	Airy-Heiskanen anomalies	VENING MEINESZ and HEISKANEN [29]
Benkulen	− 60	+ 60	120	—»—	—»—

The induced gravity change by an infinite horizontal slab is for an average value of the density 2.67 g/cm^3 g = 0.1119 milligal/metre. Thus, the differences between the gravity anomalies near the trenches show that the pressure against the flowing layer due to the mass differences is of the order of magnitude 300—1200 kg/cm^2. In these calculations it is supposed that the gravity anomalies near the trenches are developed due to such high velocity of the flowing mantle material from sea under continent that the isostasy forces have not been capacble of levelling them. The trenches show the plases of mass deficit and the surplus of mass has been collected immediately beside the trenches in the direction of the material flow. As can bee seen from

[1]) The figures are not quite comparable oving to the different reductions. Also free air anomalies are useful to show the order of magnitude of the pressure differences between ocean and continent because, due to the temperature difference in mantle, the compensation layer can extend to the astenosphere.

Fig. 3, the horizontal velocity of the flowing material is greatest below the coastline. Gravity anomalies are limited to narrow zones due to the great viscosity of the mantle material. On a large scale and over a very long period the anomalies should gradually stiffen into equilibrium unless any other changes happen. Such changes can be caused especially by the erosion on the continental area and the sedimentation on the sea area. The influence of the sedimentation is due both to the conductivity of the heat in the sea-floor, which changes the temperature conditions between ocean and continent, and to the increasing load on the sea-floor.

Great plus-anomalies have been observed on the volcanic islands. According to VENING MEINESZ and HEISKANEN [29] there is a group of oceanic islands where the difference of the isostatic gravity anomalies between the central island area and adjacent deep sea varies from 80 to 200 milligals (corresponding 200—500 kg/cm^2 pressure difference). They conclude that for most of the islands investigated the thickness of the rigid crust is about 35 km or more and that there is higher temperature below the islands. The question arises as to whether this higher temperature and raised flowing layer below the islands may be the reason why the difference of the pressure between the sea and islands displays such a great gravity anomalies. If there are no processes which change temperature and pressure differences between islands and adjacent deep sea these stabilized gravity anomalies show the equilibrium between sea pressure and isostatic forces.

I have previously presented KUTVONEN's calculations on currents of this type [14, 18], in which the difference in pressure between sea and continental area was of 20 kg/cm^2, the viscosity coefficient of the crust 10^{23} g/cm.sec, and that of the mantle 10^{21} g/cm.sec. TAKEUCHI et.al. [27] have proposed that if the findings in the three cases in which the viscosity of the crust and mantle has been determined are to be brought into agreement, we must assume that there is a more easily flowing layer about 200 km thick in the upper part of the mantle. This agrees with the seismic observations on the asthenosphere. These three cases are the Fennoscandian land uplift following the melting of the continental glacier (NISKANEN), the land uplift caused by the drying up of a Pleistocene lake (CRITTENDEN) and the flattening of the Earth caused by its rotation (MACDONALD). These studies, concerning areas of varying extent, give viscosity coefficients of 10^{22}, 10^{21}, and 10^{25} g/cm sec.

Taking these findings into account, KUTVONEN again, at my request, made calculations concerning the flows occurring in the crust and mantle [15]. It is assumed that there are four separate layers, from the surface to the lower border of the mantle, with the following depth positions and viscosity coefficients:

Depth position	Viscosity coefficient
0— 70 km	10^{22} g/cm.sec
70—300 »	10^{21} »
300—700 »	10^{23} »
700—	10^{25} »

In the calculations it is assumed that the difference in loading in the flowing layer at sea and at continent is 200 kg/cm². The calculations were carried out as a two-dimensional flow problem on a Cartesian co-ordinate system, using the order of 7 in Fourier-terms. The results can be seen from Fig. 3, when the centre of the ocean is 2 500 km from the coast. According to this, at the coastline there are horizontal speeds from the sea under the continent of over 10 cm a year from the surface of the sea-floor to the middle of the asthenosphere.

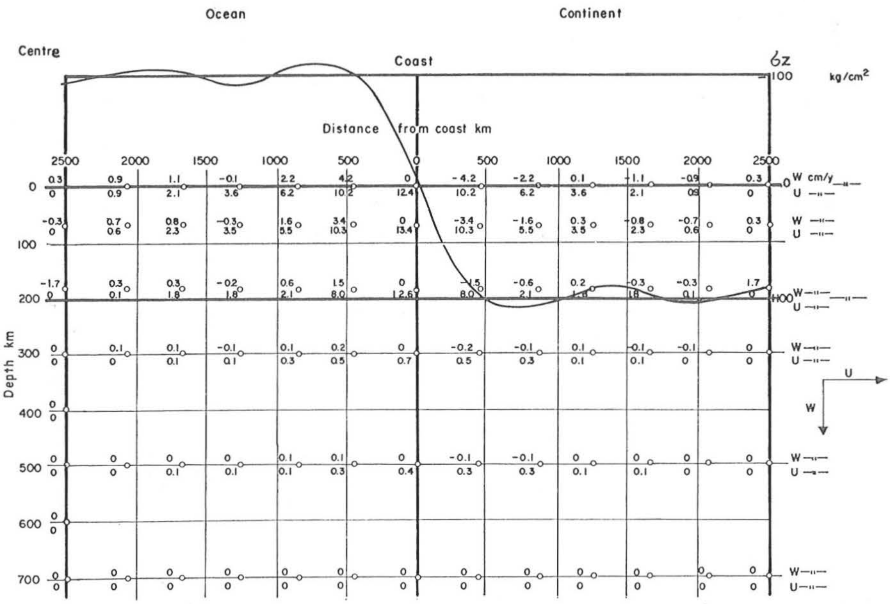

Fig. 3. Vertical (w) and horizontal (u) velocities of flow (cm/y) below the ocean and continent at various depths and at various distances from the coast. The width of the ocean is 5 000 km, the pressure difference over the asthenosphere between ocean and continent is 200 kg/cm², (the curve presents pressure model). Viscosity coefficients are in text [15]. Calculations according to Kutvonen [19].

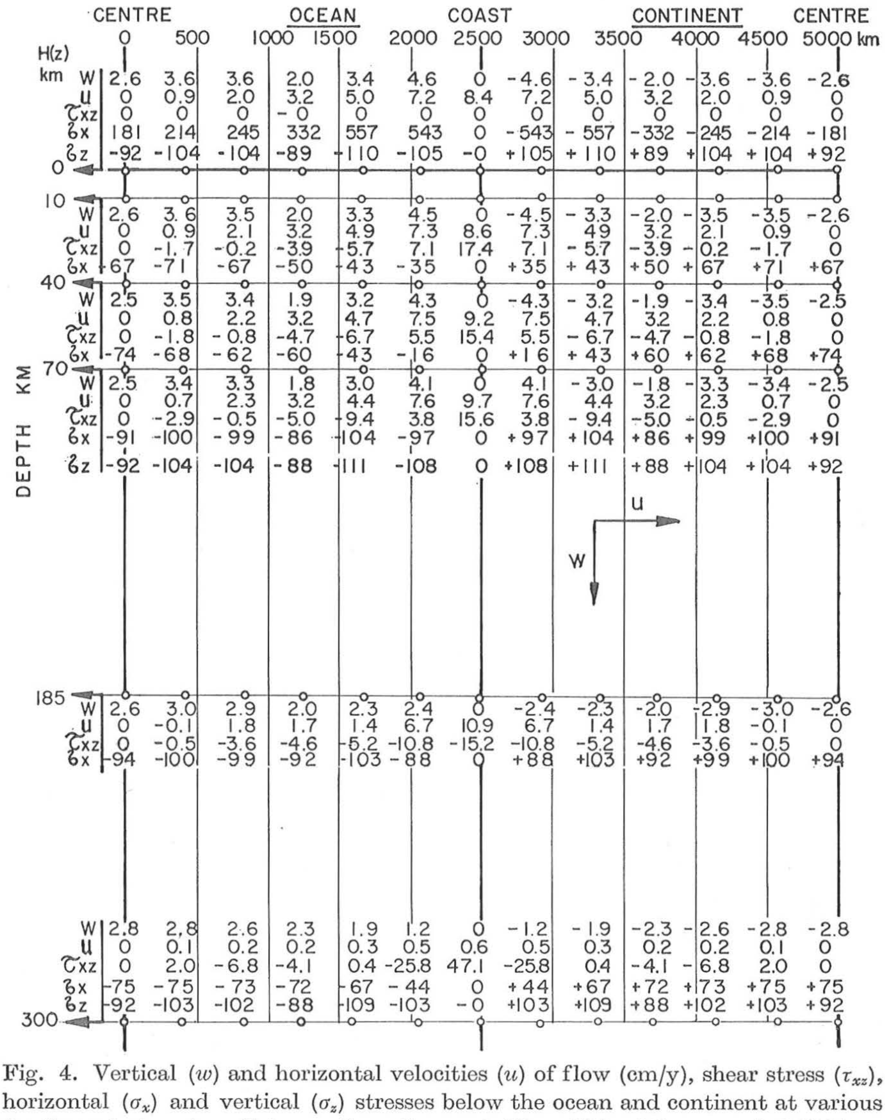

Fig. 4. Vertical (w) and horizontal velocities (u) of flow (cm/y), shear stress (τ_{xz}), horizontal (σ_x) and vertical (σ_z) stresses below the ocean and continent at various depths and at various distances from the coast. The width of the ocean is 5 000 km, the pressure difference against the asthenosphere between ocean and continent is 200 kg/cm², viscosity coefficients can be seen in the text (highest layer is 0—10 km). Calculations according to KUTVONEN [19].

The speeds decrease off the coast but they do not reach zero value until the centre of the ocean. Only slight alterations of the viscosity coefficients of the mathematical model at various depths are required to alter the results very sensitively, so there is no reason to discuss the exact figures; suffice it to observe that in flows of this type the speeds of sea-floor movements are of the same order of magnitude as in the hypothesis of sea-floor spreading. It should particularly be noted that the horizontal speeds extend far under the continent from the coast, and that vertical speeds are downward directed in the sea but upward directed in the continent.

Kutvonen [19] has developed his mathematical model so that there are four layers of different viscosity values. In this case it was not possible to use a higher order of the Fourier-terms because it is difficult to make the calculations with sufficient numerical accuracy. For the same reason it was not possible to use five layers of viscosity values. But Fig. 3 shows that even on the layer from 300 km to 700 km, where the viscosity coefficient is 10^{23} g/cm.sec, the horizontal speeds are nearly zero. Leaving out the lowest layer (viscosity coefficient 10^{25} g/cm.sec) the values of the other layers did not change very much. To bring out the influence of a more rigid crust we made calculations by using the following layers of the viscosity values:

Depth position	Viscosity coefficient
0— 10 (and 0—5) km	10^{23} g/cm.sec
10— 70 (and 5—70) km	10^{22} »
70—300 »	10^{21} »
300— »	10^{23} »

The other assumptions were the same as in Fig. 3. The results of the calculations can be seen from Fig. 4 when the highest layer was 0—10 km. The horizontal and vertical speeds of the sea-floor did not change so much that one should alter the previous conclusion. The differences can be corrected by increasing the load differences of the flowing layer between ocean and continent, because the values used are lower than the gravity anomalies near troughs show.

In Fig. 4 there are also values of the horizontal and vertical stresses (σ_x and σ_z) as well as of the shear stresses (σ_{xz}). The minus values of σ_x and σ_z mean compressive stress and the plus values tensile stress. If the max. shear stresses of a vertical become too small, for instance below ± 5 kg/cm^2, it can happen that the movement does not start. This must be taken into consideration when one makes conclusions. By making this kind of calculation in different areas where facts are available concerning the sea-floor movements, seismic soundings, loading differences (isostasy anomalies) etc. one can collect material for making conclusions on viscosity coefficients and so on.

The factors on which the speeds of movement of the sea-floor depend are linked with the differences in loading in the flowing layer under the sea and the continent. If, for example, thick unconsolidated layers of sediment with low heat conduction form at the coastline, the altitude position of the flowing layer under the sea may rise so that the difference in load between the continent is reduced or disappears, and the stress gradient becomes less steep. This may cause a new flow situation, and may explain, for example, the differences observed in the seismicity near the coasts and the rate of the sea-floor spreading for the Atlantic and Pacific oceans. Revelle et al. [25] have suggested that the catchment area in the Atlantic forms about half of the area of this sea. The corresponding catchment area in the Pacific is only a tenth of the area of this sea. This means that sedimentation in the Atlantic, particularly along the coasts, is much greater than in the Pacific.

The location of an extensive shallow sea at the coast is also a feature linked with seismically peaceful areas. Areas like this are, for example, the Arctic coastlines of Asia and North America. It is also as well to remember that because of the cold climate the permafrost extends to a depth of many hundred metres in the soil. The cold extends still more deeply in the rock. Such factors mean that the temperature rise in relation to depth in the polar areas under continent is slower than in equatorial regions, so the difference in pressure against the adjacent layer of the sea area may be less. Only a few aspects of how differences in loading in the asthenosphere can cause variation in the movement of the crust on different coasts have been put forward here.

The question of the origin of the continental slopes is also involved with continental margins. A variety of hypotheses have been proposed for this problem. At different coastlines there are continental slopes of varying origin, but in general the same type continues for thousands of kilometres in an unbroken formation. The map drawn up by Emery [5] shows that in the Pacific the most common type is one in which the sediment layer has accumulated in a trough between a rocky ridge running parallel to the coast and the continent, while the majority of the continental slope is sharply sloping rock. These rock dams, in which the rock type is of metamorphic origin or volcanic, are tectonically raised from their base. To a great extent, the continental slopes of the Atlantic and Indian oceans are sedimentation formations without any rock dam at the outer edge.

A special feature of the continental margins is that they are cut by sea canyons. These are gulleys hundreds of metres deep, running across the continental shelf and extending to the root of the continental slope. Only the largest of them are known, since the smaller ones are filled with sediments and are only observable by seismic sounding. There have been many hypotheses about the origin of the sea canyons. Probably the most widely accepted at present is that they were caused by turbidity currents [5]. Such an explanation is forced as regards canyons formed in rocks.

The sea-pressure hypothesis put forward above gives a natural explanation of the genesis of both the continental slopes and the sea canyons. The steepnes of the continental slopes, the fact that they extend to the abyssal plain, and the formation of the sea canyons can be explained by downward-directed currents of the type illustrated in Figs. 3 and 4. The rise of the rock ridges at the continental edge is explicable, in the

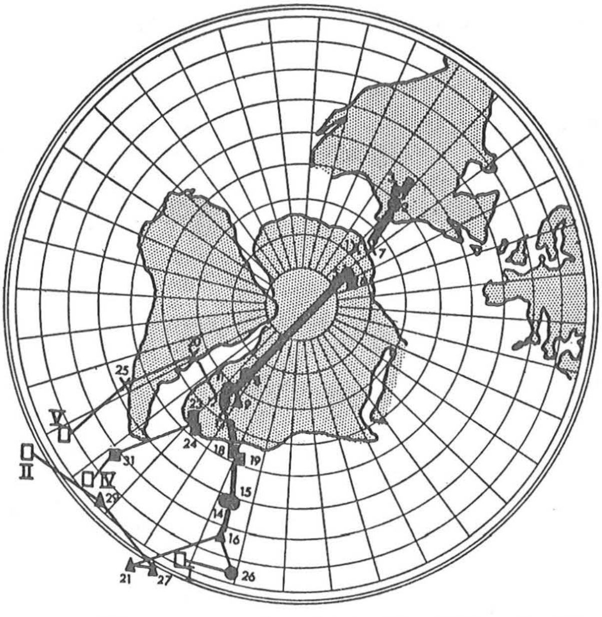

Fig. 5. Palaeogeographic reconstruction obtained by fitting the Upper Palaeozoic palaeomagnetic south poles to the single curve marked by a thick line. The order in which the present continents broke away from the large landmass is indicated by the order in which the individual polar wandering curves of South America, Africa, Europe and Russia, and North America separate from the main curve. The grid centre has no significance. According to GREER [9].

type of continental slope in the Pacific, by the upward currents illustrated in Figs. 3 and 4. The formation of the continental slopes as a whole, and as a formation extending over the entire globe, is a strong argument in favour of the sea-pressure hypothesis. Their origin cannot be explained by convection currents, and contraction or expansion hypotheses are equally implausible.

The movements of the sea floor described above raise the question of how the central ridges were formed, and of the origin of the rifts that split the continents of Gondwana and Laurasia. As regards the latter, I have proposed [14] that the Permo-Carbonic glaciation played some part in this. Fig. 5 gives Greer's [9] suggestion as to the movements of the South Pole over the continent of Gondwana about 200 million years ago. The figure is based on palaeomagnetic measurements. That stage comes just at the time which, according to the age of the sea sediments and research findings concerning continental movements, marked the first stage of the upheaval in the formation of the sea floor and the continents. The growth and melting of the polar ice sheets, some kilometres thick, that covered the continents may have been linked with events that caused currents in the crust and mantle that split even the thick-crusted continents.

If differences of loading in the asthenosphere such as are shown in Fig. 4 formed at the new coastline, horizontal tensions in the crust and mantle also occurred. The average dependence of these horizontal tensile stresses in the middle of the sea is approximately that shown in Fig. 6 when the extent of the sea area is the variable. The curves given there are calculated for the models with the viscosity coefficients as can be seen from the figure. If the highest layer is 70 km thick with the viscosity coefficient 10^{22} g/cm.sec then the maximum tension is only one tenth of the values of the curve I in the figure [15].

It can be seen from Fig. 6 that very considerable tensile stress occurs in the sea-floor in the middle of a sea area. The peak of the curves seems to be formed in a sea area about 1 000 km wide. In the depth below the most rigid crustal layer compression occurs. It should be noted that if the difference in loading over the flowing layer between ocean and continent is greater than that used in calculations the tension in the centre of the ocean is correspondingly greater.

The resistance of the Earth's crust to tensile stress is of the order of magnitude of 100—250 kg per cm^2 on the basis of Graf's estimation [8]. It can be seen that the tension at the centre is sufficent to start splitting

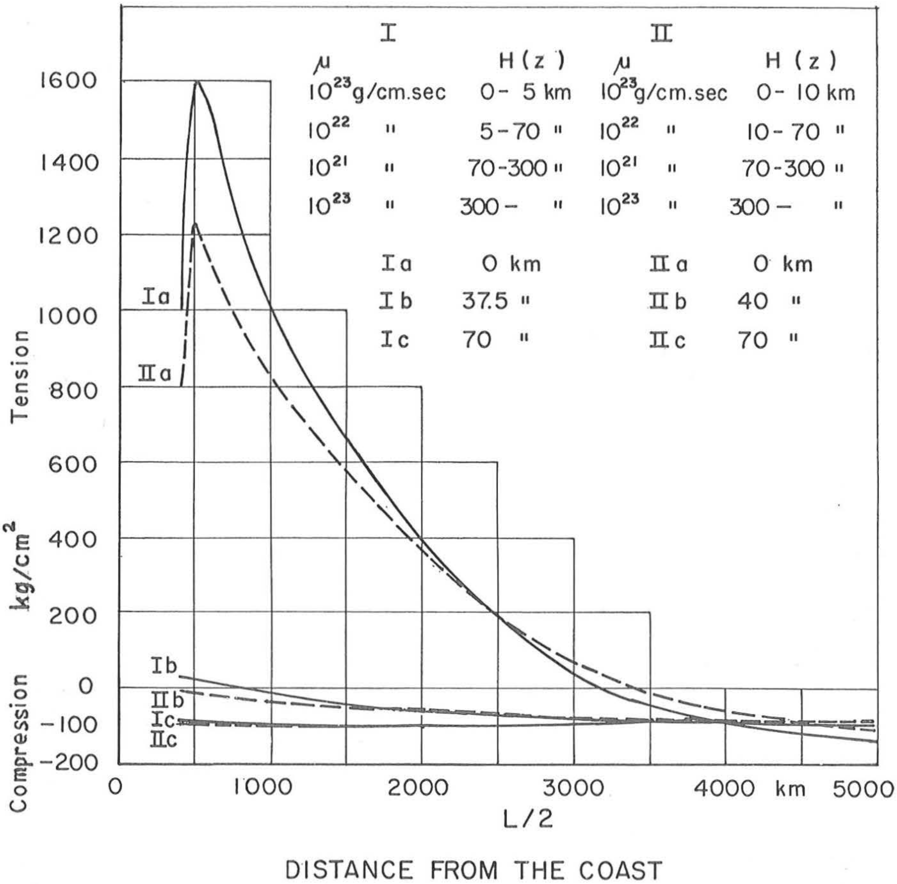

Fig. 6. Horizontal stresses σ_x (tensile + and compressive —) in the centre of the ocean when the distance from the coast varies from 700 to 5 000 km. Pressure difference is 200 kg/cm². According to KUTVONEN [19].

when the width of the sea area is not too great. Once a surface fault of this type has occurred on the sea floor the sea water, penetrating into it, causes horizontal pressure in the direction of this tension with the weight of the water layer above, acting like a wedge and trying to widen the fissure. Taking into account the deepening of the fissure due to these forces the pressure of the sea water can go up to 500—1 000 kg/cm². Sea water can also discharge tensions in the crust without great earthquakes before the resistance threshold has been reached, as has happened by pumping water into the deeper layers.

At the same time, in the flowing layer of the mantle the entire weight of the mass above causes upward-directed pressure at the weakened point of the fissure, and thus the conditions exist for the generation of a central rift of the type which in the Atlantic is situated with great precision on the sea centre. As regards its location, there are two points warranting particular attention, where the effect of the distance of the coasts seems to emerge very clearly. At the Equator, the central rift is placed along the »Romanche fault» about 800 km westward (Fig. 1). Similarly, at the Labrador abyssal plain there is a westward shift of about 600 km along the »Reykjanes fault» [23]. The interpretation of such shifts in the central rift within the convection current hypothesis has in fact been a problem that has aroused criticism of this hypothesis.

When a rift as described above has formed as a result of sea pressure, the loading and horizontal compression in the asthenosphere on both sides of the rift push flowing material upwards through the weakened crust, and a current can start moving upwards. In this movement of the warmer material, differences in temperature occur that can cause convection currents strengthening and expanding the upward flow. Phase alterations taking place in the material can also reinforce the formation of the central ridge and the turning of the flow horizontally on both sides of the central rift. Thus, closed current cells are not necessary for the continuation of the convection flow, since in the asthenosphere the sea pressure pushes the plastic material into the rising zone.

The horizontal tensile stress according to the same calculations as before, made by Kutvonen [19], has its maximum in the middle of the ocean only when the width of the ocean is about 1 000 km or narrower. Fig. 7 shows the influence of the width of the ocean on these σ_x values. The maximum of these tensile stresses diminishes when the sea sector increases but at the same time the maximum zone becomes wider. Menard [21] mentions that the central ridges of the Pacific have more gentle slopes than those in the Atlantic. This raises the question of whether the reason for these differences in the shape of the central ridges is connected with this kind of stress difference. The material flow upwards below the central rifts and pushing the sea-floor towards the continental margin obviously has a great influence upon the whole flow model, but it is not possible to make calculations of these flows due to the lack of real facts. The flow described above is in every case helping sea-floor spreading also in the centre of the sea.

When interpreting the sea-floor movements by the sea-pressure hypo-

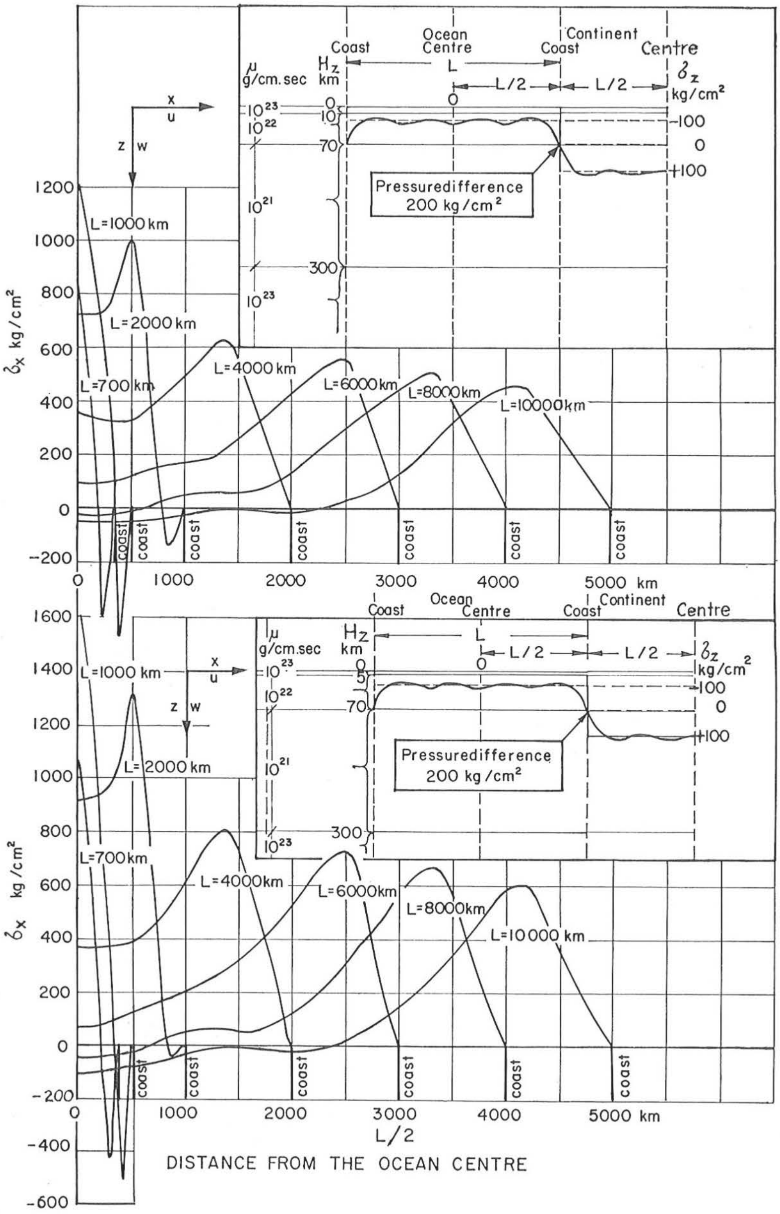

Fig. 7. Horizontal stresses σ_x (tensile + and compressive −, smoothed figures). In the upper part the viscosity coefficient $\mu = 10^{23}$g/cm.sec from the surface to the depth of 10 km, in the lower part $\mu = 10^{23}$g/cm.sec from the surface to the depth of 5 km. According to KUTVONEN [19]. Thicker rigid crust means smaller σ_x-values.

thesis a number of aspects should be remembered. Sea-pressure has an effect on a particular place also independently from that at the other places over the whole sea area. Also the velocities of the vertical and horizontal movements vary in different parts of the ocean. Many of BELOUSSOV's remarks can be answered only on the basis of these aspects. The currents in the mantle causing movements of this type are oriented according to the highest pressure gradient. Thus, the current can change direction if the pressure gradient changes. The current from a larger area may run in different directions from the different edges of the high-pressure area depending on the formation of the pressure gradient of the flowing layer in the various parts of the area. Thus, on the West Coast of North America and off the Aleutian Islands (see BELOUSSOV's criticism), for example, the sea-floor movements can happen as described according to the sea-floor spreading hypothesis. Post-Cretaceous movements of the sea-floor and the drift of the North American continent, and sedimentation, may have altered conditions in the area mentioned in BELOUSSOV's criticism so that even such apparently conflicting events as he refers to need not be in conflict with the hypothesis of sea-floor spreading, when the interpretation of the causes of the movements is right, and if one takes into consideration that the moving plates are not rigid, but different parts of the plates can move independently due to the pressure gradient. The main question is to know what actually is the mechanism behind the sea-floor spreading. For example, in the Bering Sea, EWING et al. [6] estimated the thickness of the sediment layers at up to four kilometres. During the time it took for these to collect, there was time for a variety of phases of different currents. It seems that in BELOUSSOV's criticism of the sea-floor spreading there are no points which are not explicable on the basis of the sea-pressure hypothesis. I cannot go into details, however, because I have not enough information on the conditions in different places.

I have previously put forward the supposition [14] that the sea pressure coming from the direction of the Pacific has pushed the eastern coast of Asia northwest. At the same time, sea pressure from the Indian Ocean has caused a movement of the continent northwards. The great mountain ranges of Asia and their U-shaped formations are a consequence of these movements. These movements also caused cracks in the southern coast of Asia, which appear in the spread of the Indian Ocean and the formation of the Persian Gulf and the Red Sea. These assumptions have been backed up by studies in the Red Sea area [7, 17], such as the move-

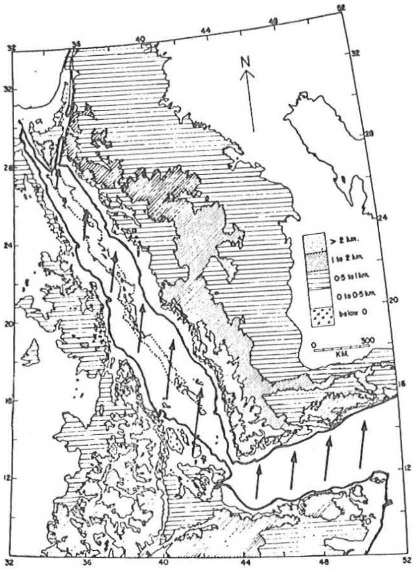

Fig. 8. Topographic map of the Red Sea area. The lengths of the arrows represent the amount of crustal separation assuming a northward translation of Arabia of 100 km and an anticlockwise rotation of 7°. According to GIRDLER [7].

ment of the north shore of this sea about 100 km to the north (Fig. 8) and the 7° movement counter-clockwise of the Arabian peninsula. The movements of the Asian continent have caused tensile stresses on the east coast of Africa, as a result of which Madagascar and the group of islands east of it have moved eastwards. OROVAN [23] criticizes the sea floor spreading hypothesis, observing that according to the hypothesis the sea-floor spreading from the central rift of the Indian Ocean should have pressed Madagascar against Africa. In addition, between Madagascar and the central rift there lies the chain of islands, the Seychelles—Amirante—Mauritius—Reunion and the wide ridge formation linking them. Neither these nor Madagascar are of recent volcanic origin, but, like Africa, Precambrian rock. According to OROVAN, this kind of conflict between the essential assumption of the sea-floor spreading hypothesis and geological facts makes the entire hypothesis unreliable. However, an interpretation according to the sea-pressure hypothesis described above is in good agreement with geological observations in this part of the globe as well.

A group of problems concerning the horizontal movements of the Earth's crust and mantle deserves consideration. If these movements do indeed occur to the extent proposed in the context of the sea-floor spreading hypothesis, this must mean alterations in the isostasy of the globe, and should be visible in maps showing the isostatic anomalies. Fig. 1 shows the map drawn up by KAULA [16], concerning geoid hights and based on measurements made gravimetrically on the Earth's surface and from satellites. Only the large anomaly waves are shown. They are not entirely consistent in detail with the gravimetric measurements. For example, in Fennoscandia there are differences, as can be seen from Fig. 9, which shows the map of gravity anomalies drawn up by HONKASALO [12]. This should be remembered when studying the geoid-anomaly humps and dells shown in Fig. 1.

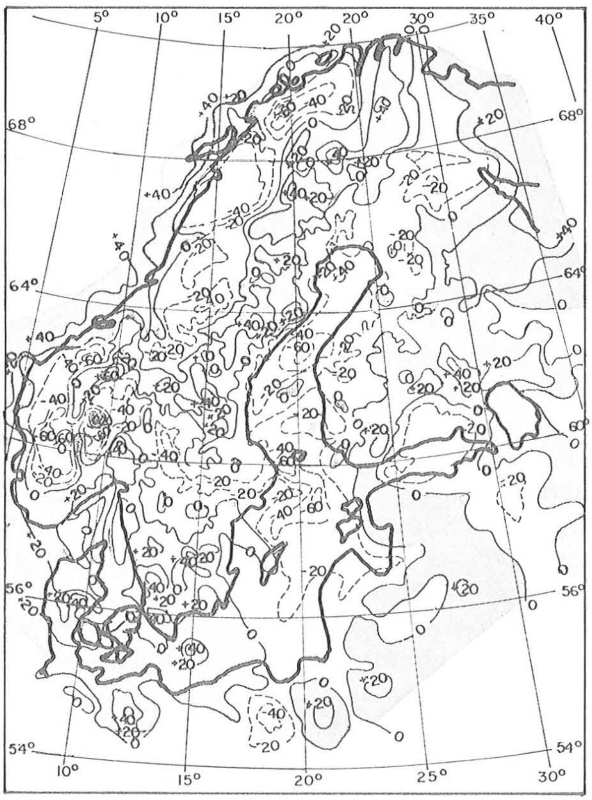

Fig. 9. Free air gravity anomalies in Fennoscandia according to HONKASALO [12].

Isostasy is a dynamic process, and as regards the movements of masses caused by sea-floor movements, it levels out the anomalous humps and dells that occur, just as it levels out anomalies caused by erosion and sedimentation. A possible explanation for the geoid highs shown in Fig. 1 is the following: The extensive high plus-anomaly southeast of Asia and north of Australia is due to pressure from the Pacific from northeast and east and from the Indian Ocean from southwest and south. In the same way, the plus-anomaly observable in western South America can be interpreted as due to the opposed sea pressure from the Atlantic and the Pacific. There is a similar wide area of plus-anomaly east of the mid-Atlantic rift. This may be a result of the flow coming from the central rift because Africa and Europe have not moved very much eastwards. This is perhaps partly due to the massive extent of the Eurasian-African continent. The Mid-Atlantic rift may itself have moved to the west, as proposed in MENARD's article [21]. The extensive plus-anomaly south of Africa and the minus-anomaly in the area of the Ross Sea, on the opposite side of the Antarctic, may be partly connected with sea pressure from the Pacific.

The largest minus-anomalies appear to form particularly in places where the continent flees from the sea because of the sea-pressure. In the Indian Ocean, an extremely marked minus-anomaly, extending far into the interior of Asia, has formed south of the Near Indian headland. The reasons for continental movement northward in Asia have already been discussed. Suffice it to add that, according to palaeomagnetic and palaeontological measurements, the northward movement of Near India during the past 200 million years from the vicinity of the Antarctic to its present position was the fastest of all known continental movements. The minus-anomaly west of the Mid-Atlantic rift may well be linked with the westward movement of North and South America.

The minus-anomaly area west of North America is probably due to the movements of the sea floor in various directions which are mentioned in the context of BELOUSSOV's criticism. Here the sea pressure causes flow towards North America, the Aleutians and Asia; the resultant vertical movement downwards in the sea-floor is so powerful that isostasy has been unable to eliminate it.

About 13.5 km^3 of the substance of the crust is annually transferred from the continents into seas due to erosion. This amount would be sufficient to fill the ocean basins in about 100 million years if there is no flow of the material from the marine areas under the continents. A part of this flow happens when the sea-floor is sliding under the continents on the areas where the trenches are traces of these movements. But there are also other indications of such movements. For example, the Fennoscandian land uplift has commonly been interpreted as a rebound after the disappearance of the ice put there by the most recent glaciation. HONKASALO has stated that gravity anomalies do not form circles around the uplift centre but are anomaly waves directed from the Atlantic towards East Karelia following the direction of the most recent old mountain ranges — the mountains of Scandinavia (Fig. 9). Nor does the concentration of earthquakes in certain areas indicate a correlation between them and the location of uplift isobases, in as much as they, too, form zones travelling in the direction of the Scandinavian mountain range. One of these follows Norway's western coastline, and another bisects the northern part of the Gulf of Bothnia from the Oslo-Gothenburg region to Kuusamo, Finland [22]. This need not exclude the supposition applying to the rebound after the disappearance of the Fennoscandian glacier, but it shows that there can be different kinds of movement simultaneously.

If the rate of sea-floor spreading is on average 2—5 cm/y and the length of the central ridges is 60 000 km, and the thickness of the oceanic crust is 5 km, then the formation of a new crustal material is 6—15 km^3/y. These figures are of the same order of magnitude as the rate of erosion. A part of this material forms new continental area, possibly as SCHEIDEGGER [26] has proposed. Without erosion and sedimentation the processes in conncetion with sea-floor spreading should have stabilized at a certain equilibrium between sea pressure and isostatic forces at an early stage of the Earth's history. Thus erosion and sedimentation also have great influence on sea-floor spreading.

There are also other processes in connection with sea-floor spreading, such as the formation of juveline water connected with the crystallisation of the mantle material. The mechanism behind sea-floor spreading which has been proposed above can perhaps help to interpret many phenomena of this material circulation.

I wrote before [14] that when dealing with the forces active in continental drift and in the origin of mountain ranges and sea-floor topography, we are scarcely concerned with a single force but with various forces acting simultaneously. This is indicated even by the extreme variety of the Earth's structure and relief. In attempts to clarify what forces give birth to mountain ranges, the part played by erosion and sedimentation has been disregarded as their influence has been assessed as too slight to bring about phenomena. Though later research is likely to cause adjustments of my assumption with regard to details, the fact that no changes have been necessary in the original basic assumption of the sea-pressure hypothesis, while new viewpoints have continually appeared on behalf of it, has convinced me that it contains a reality that could prove fruitful to research. It is possible that other forces working in the same direction will still be discovered, forces that have not been mentioned in this article.

I can still subscribe to these points of view. The supplementary factor presented in this article is the temperature difference in the mantle material between ocean and continent, which can cause much greater pressure difference against the flowing layer than I imagined.

Acknowledgments. I am indebted to the following persons for their advice and comments on this work: Drs. Väinö Auer, Tauno Honkasalo, Eino Niemelä, Erkki Niskanen and Heikki Tuominen, and Lics. Aimo Maasilta and Esko Penttilä. Civ.Eng. Heikki Kutvonen made the mathematical calculations, and I am grateful for his assistance and comments. The financial support received from *Maa- ja vesitekniikan Tuki ry.* is gratefully acknowledged.

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APPENDIX

CALCULATING MOVEMENTS AND STRESSES IN THE EARTH'S CRUST USING A TWO-DIMENSIONAL, HIGH VISCOSITY FLUID FLOW MODEL

by

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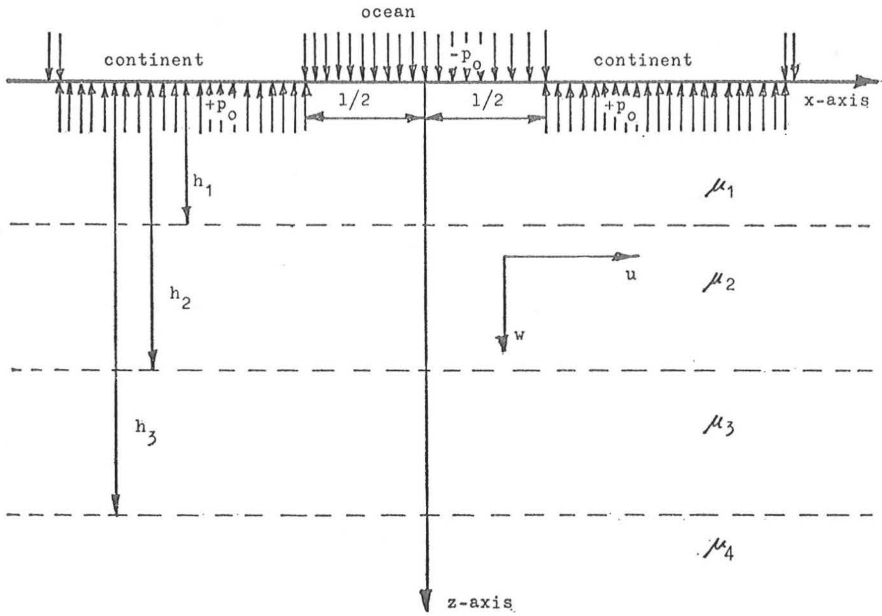
1. Mathematical statement of the problem

We assume that the earth's crust and interior are made up of many levels of varying viscosity. We also assume that the curved sections of the globe are flat. We also make the great approximation of calculating flow as two-dimensional instead of three-dimensional to make solving the problem in this case a little easier. We further presume that on top of the crust is a load with the pressure shown in Fig. 1. This load produces the movements and stresses in each viscous fluid level.

2. Differential equations on viscous fluid flow

Let us use the following identifiers: w for the velocity of viscous movement in the direction of the z-axis (vertical), u for the velocity in the direction of the x-axis (horizontal), μ the viscosity coefficient ($\mu = \nu\varrho$), ϱ the density of viscous matter and g the acceleration of the force of gravity. We can then state the differential equations of the two-dimensional viscous movement in the form (1) (Schlichting [1] p. 52 and p. 94). (Navier-Stokes differential equations and the continuity equation). In the slow flow we can omit inertia terms other than the force of gravity.



$$\begin{cases} \dfrac{\partial p}{\partial x} = \mu \left(\dfrac{\partial^2 u}{x^2} + \dfrac{\partial^2 u}{z^2} \right) \\ \dfrac{\partial p}{\partial z} = \mu \left(\dfrac{\partial^2 w}{\partial x^2} + \dfrac{\partial^2 w}{\partial z^4} \right) + g\varrho \\ \dfrac{\partial u}{\partial x} + \dfrac{\partial w}{\partial z} = 0 \end{cases} \tag{1}$$

The co-ordinate system and separate viscous layers are shown in Fig. 1.

To solve the differential equations (1) we take the flow-function ψ in the form

$$\begin{aligned} u &= \frac{\partial \psi}{\partial z} \\ v &= -\frac{\partial \psi}{\partial x} \end{aligned} \tag{2}$$

With equations (2) and (1) and eliminating pressure p, we get the differential equation for flow-function

$$\nabla^4 \psi = 0 \tag{3}$$

in which ∇^4 means the biharmonic operator $\frac{\partial^4}{\partial x^4} + 2\frac{\partial^4}{\partial x^2 \partial z^2} + \frac{\partial^4}{\partial z^4}$

We take a suitable solution from the solutions of differential equation (3)

$$\psi = -\sum_{i=1}^{\infty} \frac{1}{\alpha_i^2} [(A + B\alpha_i z)e^{-\alpha_i z} + (C + D\alpha_i z)e^{\alpha_i z}] \sin \alpha_i x \tag{4}$$

Function (4) gives us the necessary symmetric solution to w and σ_z. In function (4) A, B, C and D are the integration constants of viscous movement. These constants are also different for each index i of the series (4). The term $\alpha_i = \pi\, l/i$.

From equations (2) we now get the vertical and horizontal velocities

$$\left\{\begin{aligned} w &= \sum \frac{1}{\alpha_i} [(A + B\alpha_i z)e^{-\alpha_i z} + (C + D\alpha_i z)e^{\alpha_i z}] \cos \alpha_i x \\ u &= -\sum \frac{1}{\alpha_i} [(-A + B - B\alpha_i z)e^{-\alpha i} + (C + D + D\alpha_i z)e^{iz}] \sin \alpha_i x \end{aligned}\right. \tag{5}$$

From the second equation of (1) we get the viscous pressure p

$$p = g\varrho z + X + 2\mu \sum (B\, e^{-\alpha_i z} + D\, e^{\alpha_i z}) \cos \alpha_i x \tag{6}$$

where X is an integration constant. This can, however, be a function of x. Then we can find the solutions of the stresses in viscous fluid (magma) (SCHLICHTING [1] p. 50, KAUFMANN [2] p. 205).

$$\left\{\begin{aligned} \sigma_x &= -p + 2\mu \frac{\delta u}{\delta x} \\ \sigma_z &= -p + 2\mu \frac{\delta u}{\delta z} \\ \tau_{xz} &= \tau_{zx} = \left(\frac{\delta u}{\delta z} + \frac{\delta w}{\delta x}\right) \end{aligned}\right. \tag{7}$$

Then we get the following equations for stresses

$$\left\{\begin{aligned} &\sigma_x = -g\varrho z - X - 2\mu \sum [(-A + 2B - B\alpha_i z)e^{-\alpha_i z} \\ &\quad + (C + 2D + D\alpha_i z)e^{\alpha_i z}] \cos \alpha_i x \\ &\sigma_z = -g\varrho z - X + 2\mu \sum [(-A - B\alpha_i z)e^{-\alpha_i z} + (C + D\alpha_i z)e^{\alpha_i z}] \cos \alpha_i x \\ &\tau_{xz} = \tau_{zx} = -2\mu \sum [(A - B + B\alpha_i z)e^{-\alpha_i z} + (C + D + D\alpha_i z)e^{\alpha_i z}] \sin \alpha_i x \end{aligned}\right. \tag{8}$$

3. Boundary conditions

To determine the integration constant A, B, C, D and X we have the following boundary conditions.

In the free surface

$$\begin{cases} \tau_{xz} = 0 \\ \sigma_z = - P(x) \end{cases} \tag{9}$$

Between the separate fluid layers we must have

when $z = h_1$

$$\begin{cases} \tau_{xz_1} = \tau_{xz_2} \\ u_1 = u_2 \\ w_1 = w_2 \\ \sigma_{z_1} = \sigma_{z_2} \end{cases} \tag{10}$$

when $z = h_2$

$$\begin{cases} \tau_{xz_2} = \tau_{xz_3} \\ u_2 = u_3 \\ w_2 = w_3 \\ \sigma_{z_2} = \sigma_{z_3} \quad \text{etc.} \end{cases}$$

In (10) the indexes 1, 2, 3, . . . indicate the first, second, third, etc., fluid layers. In the lowest layer we must have a solution that disappears when z goes to infinity. From this condition we find that in the lowest layer we must have

$$C = D = 0 \tag{11}$$

in (5) and (8).

In our solution we have only one nonhomogenous term, the pressure $P(x)$ in (9). If $P(x) = 0$, then $w = u = \tau_{xz} = 0$ and σx and $\sigma_z =$ hydrostatic pressure $-g\varrho z$. This is possible in this case only if $A = B = C = D = 0$ and then we have $X = 0$. X is a constant pressure, such as the pressure of the atmosphere, and we can omit it. In further calculations we can also omit the hydrostatic pressure $-g\varrho z$, and add it to completed solutions, if necessary.

In equations (9) we assume that the pressure $P(x)$ is as follows:

$$P(x) = \begin{cases} -p_0 \text{ when } -l/2 < x < l/2 \\ +p_0 \text{ when } -3l/2 < x < l/2 \text{ or } l/2 < x < 3l/2 \text{ etc.} \end{cases} \tag{12}$$

The function of the pressure is shown in Fig. 1. We can develop the function (12) for the Fourier-series

$$P(x) = \frac{4p_0}{\pi} (\cos \pi x/l - \tfrac{1}{3} \cos \pi x/3l + \tfrac{1}{5} \cos \pi x/5l \ldots) \qquad (13)$$

and using the notation $\alpha_i = \pi l/i$, where $i = 1, 3, 5, 7 \ldots$ we get

$$P(x) = \frac{4p_0}{\pi} (\cos \alpha_1 x - \tfrac{1}{3} \cos \alpha_3 x + \tfrac{1}{5} \cos \alpha_5 x - \tfrac{1}{7} \cos \alpha_7 x \text{ etc.}) \qquad (14)$$

Now we also understand the choice of function (4). From boundary-conditions (9) and (10) we get set of simultaneous linear equations for each term of the Fourier-series (14). This set of equations has the following unknown constants:

1 fluid layer	2 unknowns
2 fluid layers	6 unknowns
3 fluid layers	10 unknowns
4 fluid layers	14 unknowns etc.

This means that we have to do a number of calculations, especially if we have many fluid layers and if we want to use many terms in the Fourier-series. This is, however, no problem using computers. There are also some difficulties in this case, as if we use 9—10 digits in calculations we cannot in some cases get results with sufficient accuracy. This is particularly the case if we have many fluid layers and we want to use many terms in the Fourier-series. It is naturally possible to use 15—20 digits in calculations with computers, but using the model in KAITERA's investigations we used 9—10 digits and 4 terms of the Fourier-series (7th degree). The reason for this is that the other weaknesses of this model are clearly greater, such as the assumptions that the surface of the earth's crust is flat, calculating in only two dimensions, omitting the isostasy, etc.

Fig. 4 in KAITERA's paper shows results of calculations, when l is 5 000km, p_0 is 100 kg/cm^2. The computer program is made using the time-sharing system of a GE-635 computer.

Acknowledgement. I am grateful to Dr. ERKKI NISKANEN for his help to find the basic ideas of this kind fluid flow model.

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