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SEA PRESSURE AS A GEOLOGICAL FACTOR

by

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Abstract

About 13.5 km^3 of the substance of the earth's crust is annually transferred due to erosion from the continents into seas. This amount would be sufficent to fill the sea basins in about 100 million years if the increasing pressure against the sea floor did not induce a flow of the material from the marine areas to under the continents. When this flow has been investigated mathematically, it has appeared that the flow lines can stretch even through the whole mantle. Flow then occurs also from below upwards. This flow again causes the expansion of the material. As the erosion-sedimentation circulation suffices to maintain the flow from the marine areas under the continents, the increased volume of the material due to the expansion is forced to rise up in the centre of the oceans. The reason for this phenomenon might be the fact that sediments accumulate to a considerable degree near coasts and that the crust on the sea is only 5 km thick whereas the continental crust is about 35 km.

The increase of sea pressure taking place evenly over the whole marine area when the amount of water increases, causes a general uplift of the continents. When the sea level is sinking the continents can be sinking too. The changes in solar radiation and albedo over the whole earth bring about the melting and growing of glaciers. This causes changes in the sea level and sea pressure and they generate accompanying currents with them caused by erosion and sedimentation. These processes work like a pump, only in one direction, because the

movements will take place irreversibly when the material of the mantle is rising to the earth's crust. The mountain ranges formed will remain as scars in the crust of the earth, subject to erosion. Nor can the continents that have been separated from each other revert to their original positions. Effects of sea pressure like these, can be quantitatively more than ten times as great as the movements caused by erosion and sedimentation.

The flow rising upwards in the centre of the oceans produces differences in the temperature of the material in the mantle, and may also induce convection flows, which can strengthen the flows started by sea pressure.

On rising into the earth's crust on the oceanic central ridges the material of the mantle when expanding pushes the sea floor towards the continents and can thus be the reason for their drifting away from each other. Foldings of mountain ranges can also be associated with movements of this kind. The powers associated with the sea pressure and the expansion of the material are great enough to achieve such movements.

The oceanic central ridges, deep-sunk seamounts, sea canyons, trenches, zones of earthquakes, the location of mountain ranges, the oldest of them being in the centre of the continents and the youngest on the edges, the observations made of the movements of the sea floor, and many other results of geological research support the new sea pressure hypothesis described above.

If the total length of the oceanic central ridges of this kind is 40 000 km and the thickness of the earth's crust in them is 5 km and only 30 per cent of the amount of the substance of the erosion-sedementation circulation rises into the crust, it induces the widening of the sea floor by 2 cm a year. Since according to GREER, Africa and South America have begun to separate from each other about 250 million years ago, this widening velocity of the sea floor suffices to separate these continents 5 000 km from each other as has happened.

The nature of the forces active in the origin of mountain ranges of different ages is one of the central problems in geology as yet unsolved, although an answer has been sought for more than a hundred years. SCHEIDEGGER (1963, p. 289) has stated that if all theories of orogenesis ever invented are re-examined in order to determine »what can be saved of them in the light of the presently available facts, it becomes immediately obvious that something fundamental is wrong with each and every of the theories.» WEGENER (1962, p. 185), in connection with his theory of continental drift, stated as follows: »The forces displacing the continents are the same as those that produce the great folded mountains. Continental drift, fractures and compression, earthquakes, vulcanism, transgression variation, and polar wanderings undoubtedly have a very remarkable causal connection. This is shown even by the fact that they increase together during certain periods of the earth's history. However, it remains a matter for the future to discover what is cause and what is effect.»

The influencing forces suggested in connection with the WEGENER's theory of continental drift have been found too weak to cause consequences of this degree. During the last years, attention has been directed for instance to the cellular convection currents. CHAMALAUN and ROBERTS (1962, p. 177—) attempted to determine mathematical rules to account for the rise of convection currents, but MACDONALD (1963, p. 602) says about these calculations: »Even if the unrealistic physical model is accepted, the treatment considers only the onset of instability. The numerical parameters used by CHAMALAUN and ROBERTS guarantee a priori a turbulent convection, so that the destruction by non-linearities 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.»

OROWAN (1964, p. 1003) made the most recent attempt to explain by the aid of convection currents the observations on the structure and the great heat flow near the crest of the mid-oceanic ridges. He started from the view that the material of the earth's mantle is crystalline and that vertical plastic convection flow occurs in it. This is conditioned by the formation, under the mid-oceanic ridges, of vertical zones having a higher temperature than other parts of the mantle. It has always been assumed, however, that hot convection currents arise under the continents and that cold currents descend under the oceans. To avoid these difficulties OROWAN supposed that »the present mid-oceanic ridges may be maintained by hot columns which originated under the primeval continent before its destruction and which still persist because of thermal inertia, in spite of the changed conditions at the surface of the earth.» This argument may arouse objections and questions.

Two years ago I presented as a working hypothesis the idea that the continuous increase of sea pressure due to erosion and sedimentation and the increase in the water volume of the seas can affect these phenomena. I have since developed this hypothesis with particular reference to the mode of action of sea pressure. The main points of this hypothesis will be presented below.

Erosion causes great changes in the earth's relief. By reducing continuously the load on the continents it causes increasing pressure against the sea floor in connection with sedimentation. KALLE (1945, p. 113—118), GILLULY (1955, p. 14), and KUENEN (1963, p. 391) have assumed fairly consistently that the quantity of erosion is at present about 13.5 km^3/yr. The main part of this amount is carried into the seas by rivers, either as solid particles or dissolved material. A smaller proportion descends from the air as volcanic dust or small soil particles loosened and transported by wind. The present amount of erosion is so great that during the last 100 million years it would represent, in the area of all continents, a layer about 9 km thick of solid rock having a density of $\varrho = 2.75$, and correspondingly 3.8 km of sediment in the area of all seas. The average depth of the oceans being 3.8 km, the ocean basins would have filled during the period stated; and during the history of the earth this would have occurred up to 30—40 times if the difference in load had not caused flow of material from the sea areas to subcontinental areas. The permanency of the continents and oceans does not support the possibility that the oceans have filled many times during the earth's history and changed places with the continents. Instead, transgressions and regressions have occurred owing to changes in sea level. It is widely assumed, of course, that the present rate of erosion is abnormal, and some scientists consider it ten times the average rate recorded during geological time. GILLULY (1949) has given reasons for thinking that it may exceed the average slightly, but probably by no more than a few per cent.

It has been assumed that sediments cause local subsidence of the crust near coasts and deltas and so would have only a slight effect on the total volume of sea basins. But it is worth noting that the sediments accumulated near coasts are in a relatively narrow zone, where the crust, owing to its rigidity, is capable of resisting local sinking to a considerable extent. It must also be taken into account that soil particles carried by water lose about 40 per cent of their weight. The sedimentation on the coasts can thus be expected to reduce the volume of the sea basins and raise the sea level correspondingly. According to KUENEN (1963, p. 545), SUESS attributed transgression to the influence of sedimentation, his contention being that the dumping of sediments into the sea must cause rise of level.

On the basis of my working hypothesis, the continuous increase of sea pressure due to sedimentation and the rising of water level in the oceans cause the sea floor to dive under the continents as will be described later in this article. This provides a simple explanation for the permanent features of the continents and oceans although the sea floor is young compared with the continents, and similarly it explains the disagreement as regards the amount of material carried to the seas under the influence of erosion and those deposited in marine areas as sediment. The sea pressure at the same time causes a slight extension of the sea floor in mid-oceanic areas where magma forces its way from deeper strata upwards.

Erosion causes a corresponding reduction of the load on the continents. It is particularly in mountain areas that erosion takes place. In this connection a continent should be dealt with as one unit.

The amount of sea water may have increased during geological time with the result that sea pressure also increased. Alterations during glacial epochs, by geological schedules, may have been very rapid. The melting of the present continental glaciers would signify a sea-level rise of nearly 50 metres, according to estimations of different investigators between 20 and 60 metres. During severe glacial epochs the corresponding changes in sea level are assumed to have been between 90 and 275 m (FLINT 1948, p. 429—437).

Many investigators assume that the water volume of the hydrosphere has remained fairly constant during geological history (UMGROVE 1948, FLINT 1948, etc.). Conceptions of this kind have been associated with the hypothesis of permanency of the continents and oceans. WEGENER, TAYLOR, etc, have put forward arguments for this hypothesis in connection with their theory of continental drift. KUENEN (1963, p. 130) has supposed that the water content of the seas has gradually increased, as shown in figure 1. The same figure also illustrates WALTHER's conception, which represents the extreme view in the direction that the

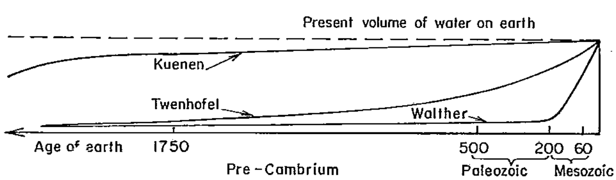


Fig. 1. Changes in the volume of the hydrosphere during the history of the earth, according to KUENEN, TWENHOFEL and WALTHER.

water volume of the seas has been formed for the most part rather late. The idea advanced by GOLDSCHMIDT seems to have been accepted, i.e. that the present hydrosphere was formed mainly during the history of the earth and that juvenile water is discharged when magma is crystallized. RUBEY (1951) and POLDERVAART (1955) and many others agree with this.

On the assumption that the formation of juvenile water has occurred at approximately even speed since the earliest times, this would represent a 100—200 m. rise of the water level of the oceans during the last 100 million years. KUENEN considers this elevation to be 20—30 m. and WALTHER almost 2 000 m.

Figure 2 shows the general influence of flow as the sea pressure increases. Viscosity is assumed to be constant in the mantle and the increase in pressure to be the same in the entire sea area. The flow is directed from the ocean to subcontinental parts while the sea pressure

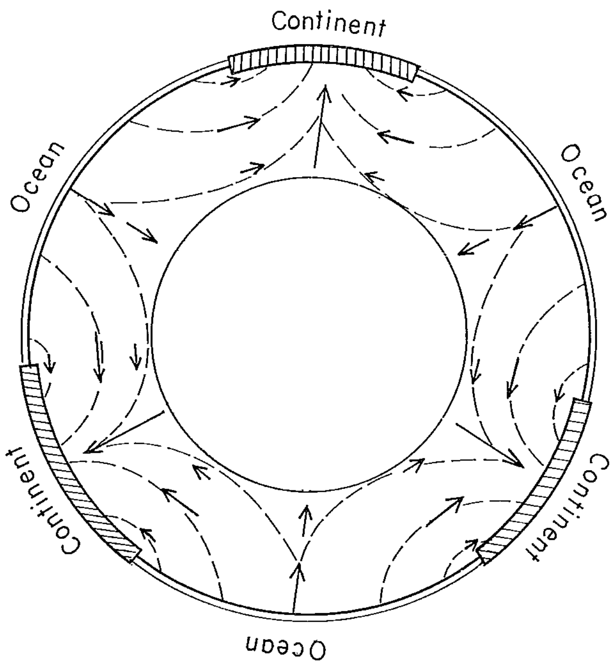
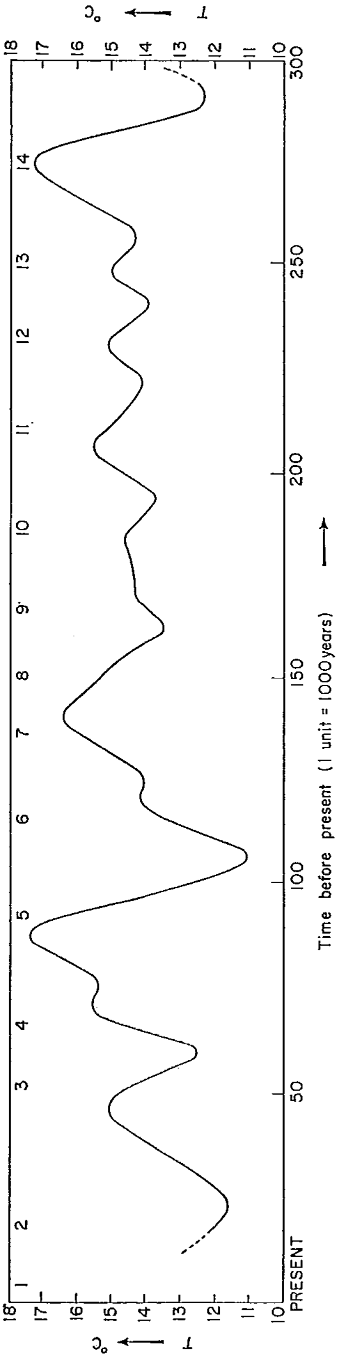


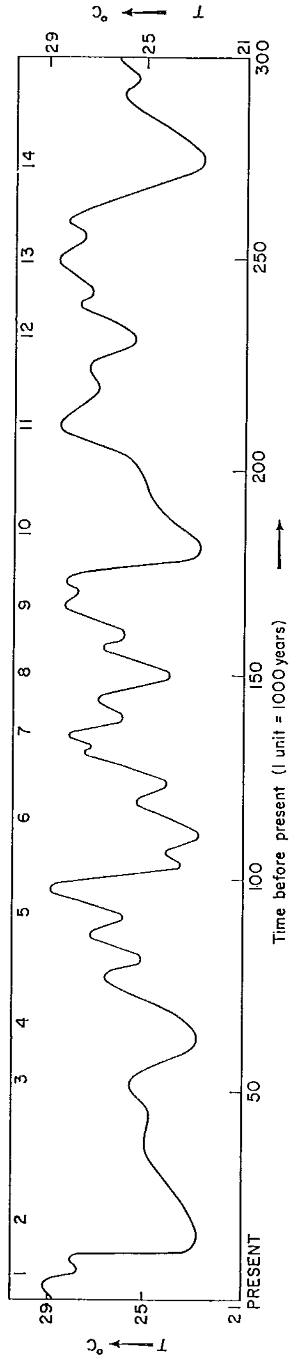
Fig. 2. Currents in the mantle caused by sea pressure, if the increase of pressure is uniform over the whole sea area and the viscosity in the mantle is constant (schematically).

causes a push which becomes increasingly effective because erosion reduces the load on the continents simultaneously. These processes, however, are much more complicated than indicated by figure 2.

In this connection, I may call attention to those changes in the amounts of water, when the glaciers increase or decrease, which are caused by changes in the solar radiation and in the albedo of the earth. As I will show later, the sea pressure may cause an upward rise of material especially in the centre of the oceans, and rising into the earth's crust. In connection with these movements, material will expand when it reaches such critical limits of temperature and pressure, where its structure changes and density becomes lower. When during the melting period the subsidence of the sea floor happens in large sea areas but the flow upwards in narrow zones, this upwards moved material will not return to its former position when sea level is lowering during the freezing period. The changes in sea level function like a gigantic pump working in certain phenomena (such as in the formation of mountain ranges and the drifting of continents) only in one direction. The expansion of the material takes place in rising zones also mainly upwards. It can not happen in horizontal direction in deeper layers because of the material in both sides does not change its volume since the changes of temperature and pressure are small. The increase of sea volume during melting periods is quantitatively and with regard to its velocity, so great that the consequential increase of the pushing forces can be up to more than ten times as great as the growth caused by erosion and sedimentation. If, for instance, the melting phase of the last glacial epoch has lasted from 10 000 to 25 000 years releasing a 50 meter thick layer water over the whole sea area, this would have meant an annual rise in the sea level of the 2—5 mm magnitude. The increase of sea pressure due to erosion and sedimentation corresponds only to a 0.1 mm rise of the sea pressure. But melting of glaciers takes place not only during glacial epochs but also at other times, as for instance presently around the Arctic Ocean, and then again at other times they will grow. The annual rise in the sea level is nowadays estimated at about 1 mm. Whether this is a consequence of an increase in the amount of water, or of something else, is a question that we had better disregard in this connection. This is, nevertheless, indicative of the possible magnitude of the fast eustatic changes of the sea level. We can get a picture of the climatological changes and their magnitude and speed that cause these changes during the last 300 000 years, from figure 3, which shows the results of EMILIAIN, that



Temperature oscillations from Pleistocene mid-Atlantic core No. 280 measurements on *Globigerina inflata.*



Generalized Pleistocene temperature oscillations for tropical surface waters (after C. Emiliain).

Fig. 3.

are based on combined deep-sea core observations (NAIRN & THORLEY 1962, p. 168).

With the object ascertaining whether increased sea pressure against the sea floor causes viscous flow from the subocean region towards the continental margins, I requested Professor ERKKI NISKANEN to make preliminary calculations. Starting from Navier-Stokes differential equations, omitting the terms of inertia and assuming that mass forces are due to gravitation alone, he investigated the movement as stationary flow of viscous incompressible fluid. For greater simplicity the calculations were carried out as a two-dimensional flow problem in a Cartesian co-ordinate system. The directions of co-ordinate axis and those of forces p_0 are shown in figure 4; u denotes horizontal velocity and w vertical velocity, τ_{xz} is shear stress and μ = viscosity. The following formulas were deduced:

(1) $$\tau_{xz} = -2\,\alpha_1^2 A_{1ze}\, ze^{-\alpha_1 z} \sin \alpha_1 x\ ;\ A_1 = \frac{2}{\pi^2} \cdot \frac{p_0 l}{\mu}$$

(2) $$u_1 = \frac{2p_0}{\pi\mu} \cdot ze^{-\alpha_1 z} \sin \alpha_1 x$$

(3) $$w_1 = \frac{2}{\pi^2} \cdot \frac{p_0 l}{\mu} \cos \alpha_1 x$$

These are the first terms of the quantities in question computed by the aid of Fourier series.

One feature in these formulas deserves particular attention. The amount of the produced shear stress and also of the velocities are almost

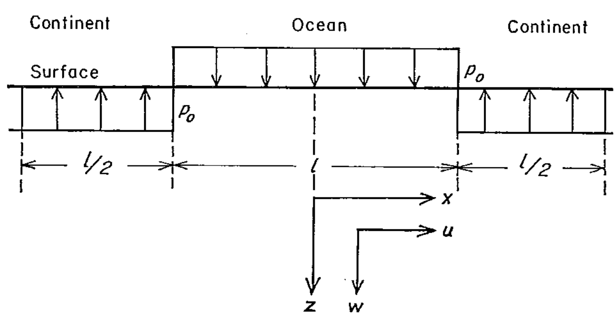


Fig. 4. The directions of the co-ordinate axis and the p_0-forces in the calculations carried out by NISKANEN.

directly proportional to the size of the sea area (l = length of the sea sector). In the Pacific, the length of a sea sector like this can be more than 10,000 km, or 2—4 times as large as in other oceans. The calculations should then be carried out in the spherical co-ordinates, but these attempts seem to lead very lengthy calculations. A study of these equations shows only that the qualitative influence in great features is similar to that obtained when using a rectangular co-ordinate system. The huge size of the Pacific may partly be responsible for the fact that the Alpine mountain ranges are situated mainly on the coasts of the Pacific.

HEIKKI KUTVONEN, Civil Eng., has completed these calculations and assumed that there are two layers with different viscosity in the upper part of the earth and that the pressure, owing to sedimentation, is greater near the continents than in mid-oceanic areas. The calculations will be dealt with in a separate article attached to this paper. Figure 5 gives the results of his calculations based on the following assumptions: The length of the sea sector is 3000 km. Total pressure is the same in case a and b. There is a pressure maximum near the coasts, so that its ratio to the pressure minimum in mid-ocean in case a is p_{max}: p_{min} = 1.4, and in case b $p_{max} : p_{min} = 10$. Mean pressure is 10 kg/cm². In the upper layer, which is 5 km thick, $\mu = 10^{23}$ g/cm s and in the lower layer $\mu = 10^{21}$ g/cm s.

Figure 5 shows the distribution of the sea pressure p in different parts of the marine area, using the two terms of the Fourier series. The figure also indicates the subsidence of the sea floor taking into account the isostatic balance (solid line beneath 0-level) as well as the sinking caused by sea pressure obtained by distributing total sinking in relation to the calculated vertical velocities (dashed line beneath 0-level). In case a the total sinking produced by sea pressure is 11 per cent greater than in case b.

In case b, the sinking due to sea pressure is found to be greater in the centre of the ocean than presupposed by the isostatic pressure. There is a constant tendency towards isostatic balance, and therefore the sediments near the coasts cause greater sinking of the sea floor than would be expected on the basis of sea pressure. It is observed that sea pressure gives rise to other kinds of flow of material in the mantle than do the forces producing isostatic balance. The isostatic forces cause the formation, in the centre of the ocean, of a region where the stream lines are directed upwards more easily than in other parts of the oceans. If

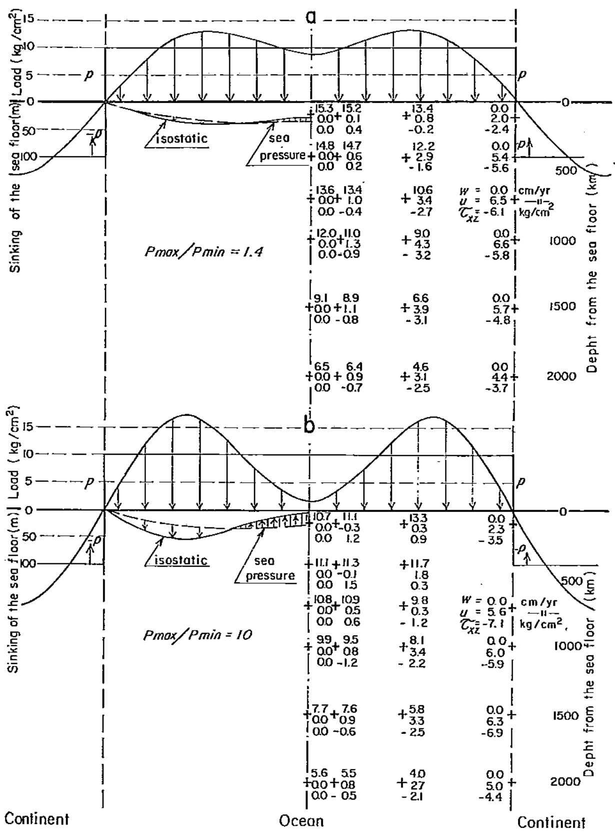


Fig. 5. Two different distributions of sea pressure: a) $p_{\max} : p_{\min} = 1{,}4$, b) $p_{\max} : p_{\min} = 10$. The dashed line below the 0-level indicates the sinking of the sea floor as a consequence of sea pressure, whereas the solid line indicates the sinking of the sea floor as a consequence of isostatic forces. Numbers on the right half indicate velocities and shear stresses caused by sea pressure at different points, μ being equal to $10^{21} - 10^{23}$ g/cm s. w = vertical velocity, u = horizontal velocity, τ_{xz} = shear stress. It appears that currents arise throughout the mantle. Calculations by H. Kutvonen.

sea pressure is evenly distributed throughout the sea area, this kind of effect does not arise.

In the right half of figure 5 are seen the values of w, u and τ caused by sea pressure. These values show that the influence of sea pressure can extend throughout the entire mantle. Flow then occurs also from below upwards. In the presence of an upward flow, the mantle material expands, and the amount of this expansion can be estimated on the basis of the decreased density of material. As material rises from a depth of 2500 km to the crust its volume increases about 100 per cent owing to the decrease of pressure and to crystallization; from a depth of 700 km the increase in volume is about 60 per cent (SCHEIDEGGER 1963, p. 55). The average volume increase by building of the sial crust is about 15 per cent.

The flow of material to under the continents may also be caused by an increase in sea pressure connected with the melting of glaciers; thus, the flow of material caused by sedimentation may be directed mainly towards the oceanic central ridges and expanding, may become greater in volume than the amount of material in the erosion-sedimentation circulation.

Thus, in addition to the erosion-sedimentation circulation, another circulation of material is set up in the mantle. Another contributing factor is that, as material pushes towards the interior, it expands, with increasing heat, to the extent that in spite of increased pressure only partial decrease in volume takes place (SCHEIDEGGER 1963, p. 95—96). Such a diving of material towards the earth's interior seems to occur in zones of deep earthquakes. In deeper layers the increase of pressure may restore the structure of the material as it was during the rising phase and cause contraction but this may take place in greater depth than the expansion into the same structure.

The special features described above might contribute to the formation of central ridges. Active in their formation are the pushing forces produced by the expansion of substance as it rises from deeper layers to the crust. The sea floor begins to rupture and more material to dive into the sea floor from below. These forces and the expansion of material displaces the sea floor and the layers beneaht it from the central ridges in both directions towards the continents. The rising of material from below into the crust occurring in mid-ocean, but not in mid-continental areas, might also be promoted by the fact that the crust on the sea floor is only 5 km thick whereas the continental crust is about 35 km.

The upward flow on the central ridges might occur very slowly at first. It even seems that the formation of the new central ridges requires special circumstances which will be explained later on.

The upward flow of material in mid-ocean ridges can also be supported by the forces possibly causing thermal convection currents. Assumptions of this sort regarding convection currents are rather hypothetical, and in the sea pressure hypothesis the forces and distances of movement are sufficient even withouc them. I have only wanted to point toward this possibility, because many scientists have attached such great importance to the convection currents. If such currents actually exist, then sea pressure may conceivably be an initiating force. These circulations seem thus to occur especially under the seas and to rise upwards in the centre of the oceans.

As evidence that even continental drift can be explained on the basis of the sea pressure hypothesis let us assume that the amount of material rising into the crust in mid-ocean is only 30 per cent of the volume of the erosion-sedimentation circulation. If the total length of the central ridges is 40 000 km, then the horizontal expansion of the sea floor is about 2 cm per year in a crust of 5 km thickness. If the separation of South America and Africa began about 250 million years ago (GREER 1964, p. 1119) the continents might have drifted about 5 000 km apart under the influence of the push associated with the enlargement of the sea floor. This is actually the present distance between these continents of the South Atlantic. The expansion of the sea floor may be unevenly distributed, being greater than the mentioned amount in some marine areas and smaller in others.

The pushing forces generated as material enlarges are thousands of kilogrammes per cm^2. They are able to push mountain ranges into folds, and even continental drift thus becomes possible. The crust of the central ridges, too, tends to fracture and folding into mountain ranges occurs. It may be noted that earthquake foci appear in central ridges at a depth of less than 65 km (SCHEIDEGGER, p. 58), which is in accordance with the pictured currents. As the crust moves away from the central ridges, the inequalities of the sea floor are smoothed out owing to sedimentation and isostatic forces. Abyssal plains have a relief of this kind.

The exceptional conduction of heat observed in the central ridges (HEEZEN 1962, p. 271) shows that heat flow is included in these movements. As hot material moves away from the central ridges, it is cooled. Not only the crust of the sea floor but also the underlying material may drift away from the central ridges. Sea pressure alone is sufficent to generate a current in a layer about 50—100 kilometers thick. The sea deepens because denser material from below mixes with the moving material. The enlargement of the sea floor can push the sediments to mountain ranges on continental margins. Indeed, the near the coast, the younger are the mountain ranges of the continents (MAGNUSSON 1960, p. 413; TERMIER and TERMIER 1956, p. 300) as it can be seen in the figure 6. This agrees with the continued formation, due to pushing forces from

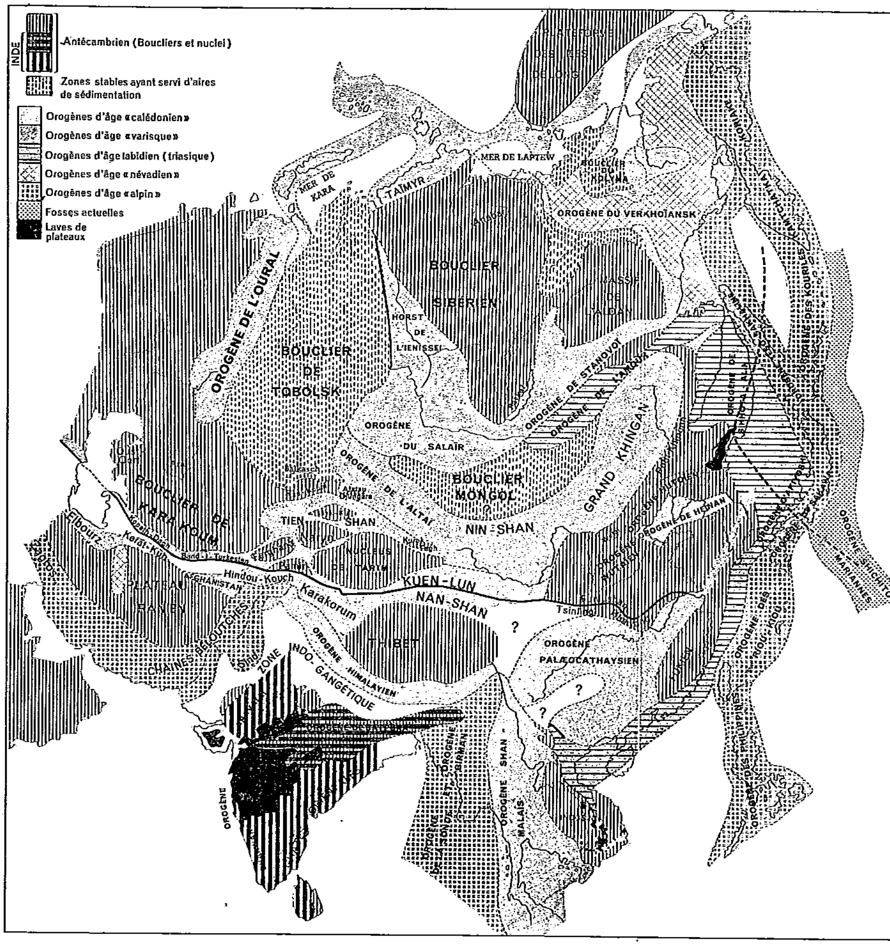


Fig. 6. The mountain ranges of Asia according to TERMIER & TERMIER. The nearer the coasts the youngar are the mountain ranges. Note also the variety of the structure of the continent.

the oceans, of mountain ranges adjoining each other. In addition, the mountain ranges are composed to a considerable extent of such thick sediments as are deposited near the continental margins. On the basis of the sediment structure of the mountain ranges, there has been developed the concept of geosynclines — deep and narrow throughs with heavy deposition of sediments. SCHEIDEGGER (1963, p. 18) states that »the occurrence of a geosyncline is an entirely hypothetical assumption, but it is made plausible by the observation that, in mountain belts, the thickness of the sediments must have been tremendous.» The fact that coastal sediments occur in zones of the type the geosynclines have been assumed to represent is well in line with the above description of the nature of the pushing forces.

It may be also assumed that at a certain depth there is a horizontal layer of a certain thickness which begins to flow under lower stresses than the layers above and beneath it. These layers can then be compared to rigid plates pressed against one another so that the »plastic layer» between them begins to flow. On the basis of what has been said above, this kind of movement can occur on the continental margin when erosion reduces the load on the continent and heavy sedimentation occurs on the coast. According to PRANDTL's (PRAGER & HODGE 1951, p. 152) equations, this kind of effect can be limited to narrow zones near the coasts. This kind of marginal effect might explain for instance the formation of the continental slopes and the fact that the sea floor subsides under the continents.[1]) SHEPARD (1948, p. 194) has advanced a number of reasons why faults can be considered as having caused continental slopes. This kind of flow also provides a natural explanation of the sea canyons in the continental slopes. Several explanations of their origins have been presented but the question still is open.

CHADWICK (1962, p. 216) reports that the long-term rheological behaviour of the crust and outer mantle in shear can be idealized as that of a material which possesses a stress threshold, below which it is perfectly rigid and above which flow takes place, the stress in excess of the yield value then being proportional to the rate of strain. The viscoplastic material characterized by these properties is known as a Bingham solid. The above rests on the assumption that the material of the crust and mantle follows the rules of both viscous and plastic flow. Material may be crystalline under the Moho-discontinuity, so that in this layer, plastic flow may be possible. Plastic flow starts when the stress in this layer increases and unsettles the balance obtained to the extent that the stress threshold of plastic transformation is exceeded. Viscous flow can take place throughout the mantle owing to the large size of the sea area,

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[1] During the printing of this article I received from Dr. J. GILLULY a reprint of his paper (GILLULY 1964) where he referring among others to my paper (1963 b) writes: »I suggest that the thinning of the crust toward the foot of the Continental Slope is a result of subcrustal erosion by the mantle current, localized by the sedimentary load.»

as can be seen in figure 5. Thus, in the above assumptions, rheological behaviour in the mantle has been nearly the same as in the Bingham solid.

Below, attention will be drawn to a few of the numerous observations supporting the above-described movement of the sea floor from the central ridges towards the continents and the pushing of the sea floor towards sub-continental parts.

Direct observations of extensive sea-floor movements approximately vertical to the coast have been made on the west coast of North America (HEEZEN 1962, p. 249). DIETZ (1962, p. 297) says of these movements that apparently the sea floor »may slip under the continent without any strong coupling. Another aspect is that the magnetic anomalies smooth out and virtually disappear under the continental shelf; so the sea floor may dive under the sial and lose magnetism by being heated above Curie point.» At certain places the zones of deep earthquakes directed to under the continents on the continental margins indicate the zones where movement of material towards the centre of the earth is taking place (BENIOFF 1962, p. 127). When the sea floor dives under the continent, the thin crust partly accumulates under the continental margin and this accounts for the difference in the thickness of the sial crust under the oceans and continents.

The structure of the central ridges of the oceans and seismic areas near the ridges (HEEZEN 1962, p. 256—258; SCHEIDEGGER 1963, p. 58) are in good agreement with the mechanism described above and with the observation that, the farther they lie from the central ridge, the older the islands of the Atlantic and Indian oceans are (WILSON 1963, p. 94). WILSON considers that the velocity of the movement is about 2 cm per year, the maximum being about 6 cm per year.

In the Pacific, WILSON assumes movement to take place on either side of the East Pacific Rise. In the North Pacific, it is directed towards the Aleutian and East Asian Trenches. DIETZ (1962, p. 296) states, also on the basis of seamounts, that »all may be moving into the Western Pacific Trenches. Seamount GA-1 south of Alaska may be moving into the Aleutian Trench.» San Andreas strike-slip fault also shows this movement (BENIOFF 1962, p. 107—114) and agrees even in small details with the foregoing.

When speaking of the guyots of the Pacific, DIETZ states that the oldest among the seamounts, the Mid-Pacific Mountains, are Cretaceous. In analysing the various seamount groups of the western Pacific, he concluded that none of them was older than mid-Mesozoic. The young age of the seamounts has been a puzzling problem. The puzzle dissolves, however, when one assumes that sea pressure causes the floor to subside. KUENEN (1963, p. 397) quotes HESS as stating that the summit depths of the seamounts of the Pacific vary from 940 to 1730 metres at least. But future soundings may be expected to detect even deeper summits: indications have already been obtained of guyots having depths between 2000 and 3400 m. The very location of the seamounts with flat summits, so deep considering their youth, favours such sinking of the sea floor as would be expected on the basis of the sea pressure hypothesis. The flat summits of the seamounts are assumed to have formed on the sea surface and their varying depth shows that subsidence of the floor has occurred differently in different places.

If the movement of the sea floor in the Pacific has occurred from the East Pacific Rise towards the Aleutians and the east coast of Asia, the exceptional length of the dislocation distance might cause the northern part of the Pacific to be deeper than other oceans, because mixture of dense material from below with the moving material has occurred to a greater extent than under other oceans.

To turn to matters having a closer relationship to Finland, I wish to add a new aspect of the uplift in Fennoscandia to those earlier presented on its mechanism. The occurrence of the uplift has commonly been interpreted as a rebounding after the disappearance of the ice put there by the most recent glaciation. However, this interpretation has recently been questioned among others by Russian investigators, who claim that the uplift occurred also before the onset of the last ice age (SCHEIDEGGER 1963, p. 46). According to ESKOLA (1950, p. 352), the Caledonian mountains in Scandinavia, after having descended in the Devonion period, have again risen to form mountains in the Tertiary. If it is a question of reduced load due to recession of glaciers, the negative gravity anomalies should be approximately uniform with the isobases of land uplift. HONKASALO (1960, p. 117) 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. Nor does the concentration of earthquakes to 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 (MIAMURA 1963, p. 200).

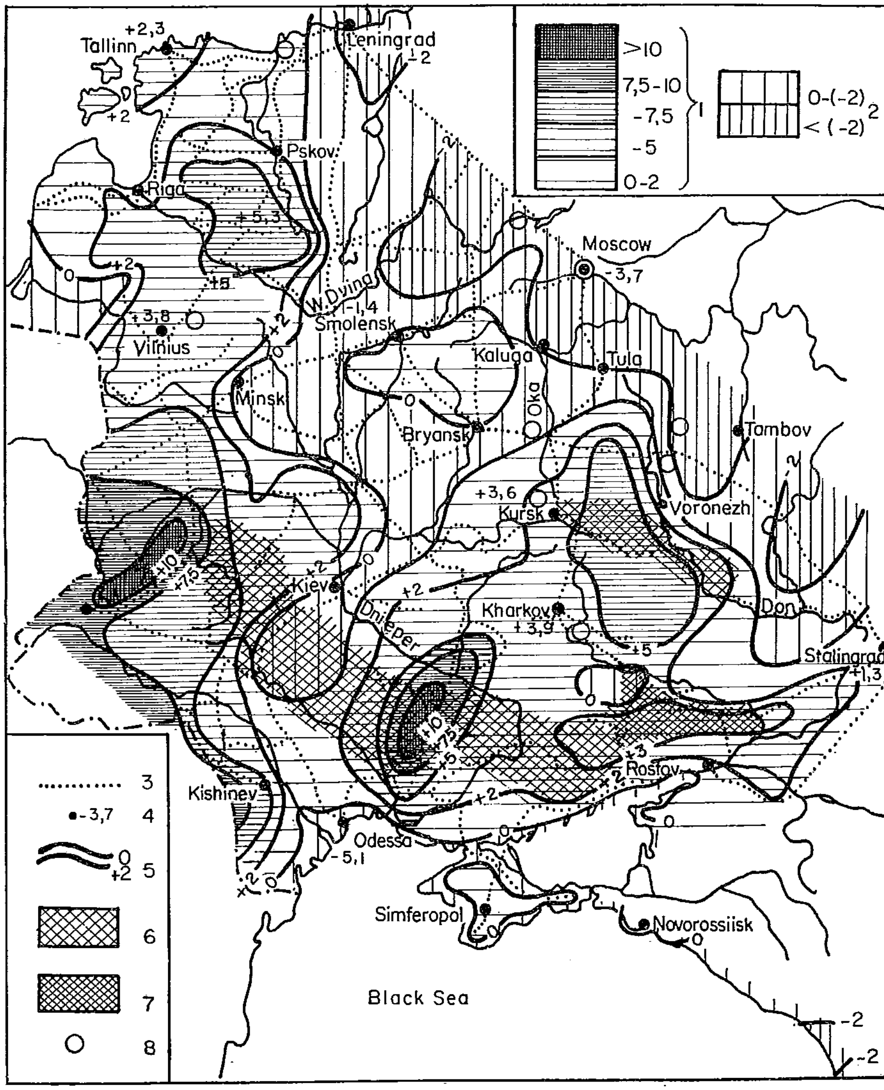

Fig. 7. Land uplift and subsidence areas in the western part of European USSR according to MESCHERIAKOV. 1. = land uplift mm/yr., 2. = land subsidence mm/yr., 3. = levelling lines, 4. = land uplift (+) or subsidence (—) in a point, 5. = isobases, 6. = visible crystalline rocks in Ukraina and Voronesh, 7. = visible Palaeozoic rocks (Donetz faulting), 8. = main epicentre areas of earthquakes.

If the uplift of Fennoscandia was caused mainly by the removal by melting of the load caused by the continental glacier, then the uplift ought to end somewhere in Estonia. The investigations of ZELNIN (1957) and MESCHERIAKOV (1958) indicate that the zone of uplift continues from Estonia down to the Carpathians. The figure 7 shows a map by MESCHERIAKOV on the movements of the earth's crust in the western part of European USSR. The levellings were done in 1913—1932 and 1945—1950, and were fixed at sea level in Tallinn, Memel, Odessa, and Kertsch. According to the map, the continental uplift zone extends from the Carpathians to north of the Black Sea, being nearly the size of Fennoscandia. Correspondingly, to the north-east of this zone is a vast area of subsidence clearly extending north-east of the line Leningrad—Moscow—Stalingrad. The map shows that the magnitude of uplift in the Carpathians and the Krivoi-Rog area reaches 10 mm annually, or is of the same class as the maximum uplift in Fennoscandia. As these Russian uplift areas are located outside the areas covered by the continental glacier, the reason for their rise cannot be the decrease in the load caused by the melting of the glacier.

Having established that secular movements of the earth's crust such as these are too fast to have been going on very long in the same direction, MESCHERIAKOV assumed that they may have been composed of several wave-motions the period of the shortest varying from a few decades to a few millenniums, while the period of the longest may be 150 million years. When in many instances the elevated shields of the earth's crust are still rising and low lands are subsiding (indeed, there are several exceptions to these rules), MESCHERIAKOV assumes that »the causes of the present motions are to be found from the same phenomena that have shaped the geological structure of the earth's crust and relief. They are above all tectonic processes taking place inside the earth in interplay with the differentiation of the substances in the crust, the motions of the magma, and other phenomena as yet little known.» These conclusions do not preclude the possibility that the uplift of Fennoscandia may have a glacioisostatic character, but this factor appears secondary.

Further, MESCHERIAKOV notes that the areas of uplift and subsidence form something akin to large waves, which largely follow the direction of the meridian. An uplift area of this kind is the Estonia—Carpathians area, which in the south extends to the Black Sea, and in the North is connected with the Fennoscandia area. East of this area is a subsidence area, also running in the direction of the meridian. MESCHERIAKOV professes to have found a similar wave of uplift in the zone of the British Isles and the Iberian Peninsula.

In Fennoscandia or European USSR there is no area of importance totally lacking in secular epeirogenic motions of the earth's crust. In USSR the land rises on the average of 2—3 mm annually when the subsidence is also included. Erosion and sedimention can cause an uplift averaging 0.1 mm on all continents. But, for example, the present eustatic rise in the sea level of 1 mm annually can cause a 1 mm annual rise of the continents. If the assumption of MESCHERIAKOV is right, that the secular motions of the earth's crust are composed of several waves with a varying period, we can imagine, according to the sea pressure hypothesis, that the erosion-sedimentation circulation is the cause of a long period, and that the changes of sea level are the causes of secular motions having also its effect to the long periods. It is to be noted that in the erosion-sedimentation circulation also, the masses are so great that if its effect had been concentrated on the formation of the Alpine mountain ranges, these could have risen to their present altitude in a couple of millions of years. As this phase of mountain ranges folding is known to have lasted for 60 million years, this indicates sea pressure to be sufficient to cause even phenomena like these, although rapid secular epeirogenic motions may take place concurrently. According to the sea pressure hypothesis, epeirogenic and orogenic motions have the same basic cause; this is also supported by the concluions of MESCHERIAKOV about the causes of secular motions observed in European USSR.

Looking at the matter from the angle of the sea pressure hypothesis, attention should be paid to the following features: In Iceland on the Central Atlantic Ridge rifts in the crust are noted also on the earth's surface (HEEZEN 1962, p. 264), which suggests a sea floor displacement of the kind already described. This push coming from the sea may cause a wavelike rise and subsidence of the earth's crust. This assumption is supported by the earthquake and uplift waves having the same direction as the Mid-Atlantic Ridge. HONKASALO states that co-operation of various branches of geophysics evidently will lead to the best result in elucidating the uplift in Fennoscandia. The above points seem to suffice to show that a push from the Atlantic direction should also be considered in dealing with these questions.

I have endeavoured to outline the movement of continents after the Permian epoch, taking into account the spreading of the ocean away from the central ridges and starting from two hypotheses made by

WILSON (1963, p. 96), apparently in agreement with mine: »at first that where adjacent continents were once joined a median ridge should now lie between them; second, that where such continents are connected by lateral ridges they were once butted together in such manner that points marked by the shoreward ends of these ridges coincided.»

Thus Kap Pria on the west coast of Africa and Sao Paolo on the east coast of South America would have coincided near Tristan da Cunha. Gaussberg in Antarctica and Cape Naturaliste in Australia would have coincided near Amsterdam Island. On these assumptions, the position of the Gondwana continents is nearly the same as presented by WEGENER, except for the presence of a large sea in the middle of these continents (see also TING-YING H. MA 1960, p. 113—115). If WILSON's map of the directions of movement of the Pacific sea floor is right, then Alaska and Kamchatka during the Permian epoch would have been farther south than today. Eastern Asia would have moved north-westwards. At the same time the Indian Ocean would have pushed the continent northwards. The mountains of Asia acquired their U-form through being pressed around the Siberian shield (fig. 6). The mountains in the middle of the continent (the Urals) conform to the stated directions of the pushing forces. These movements also caused ruptures in the continent, such as the Persian Gulf and the Red Sea. The formation of Rift Valley in East Africa may also have begun in connection with these movements.

In the case of North America, too, the picture provided by the sea pressure hypothesis of the shape and position of the continent during the Palaezoic differs from that assumed by others (WEGENER, WILSON). The north-western part of the continent has moved northwards more rapidly than the south-western part. The temperature curves of DURHAM (CRAIG 1961, p. 220) accord with this well. Thus, the north-western part of the continent has turned clockwise around the central part. As a result of this movement shear forces have been set up on the west coast. San Andreas fault, California Bay and the ruptured forms of Central America are indicative of possible movements of this kind. On the east coast of the continent, the northern parts of the Appalachians, connected with Europe in the past, have moved more rapidly northwards than the southern parts.

KING (1961, p. 322) supposes that the south pole during the Permian was situated in the middle of Antarctica. On this assumption, Antarctica would have lain about 30 degrees towards Africa and India calculated from its present location, and the south pole would have moved accord-

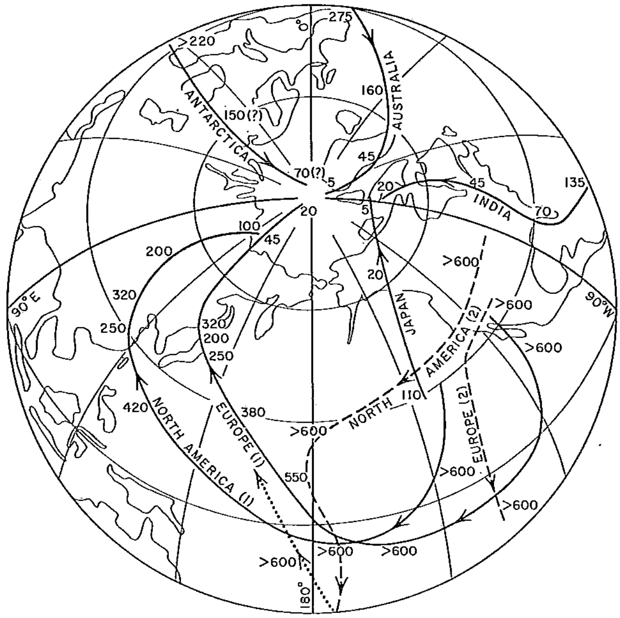

Fig. 8. Paleomagnetic polar wandering curves proposed for Antarctica, Japan, India, Australia; and two sets of curves for Europe and North America. Numbers adjacent to paths indicate approximate age in millions of years of some of the formations from which paleomagnetic data were derived (according to DOELL & COX).

ingly. There are investigations, however, supporting the idea that movement of the poles has been very slight during the last 250 million years. For instance DOELL and COX (1961, p. 298) have published a map (fig. 8) showing the movements of the north pole observed in different continents on the basis of palaeomagnetic studies. There being only one north pole, its movements cannot be along many different paths. This map, then, allows no rational interpretation if one supposes that the north pole alone has moved. But assuming that the movements of the north pole have been relatively slight during the last 250 million years and the continents have drifted northwards and also westwards from the Mid-Atlantic Ridge in the case of North America, and also eastwards in the case of Europe, and if — in addition — certain torques have taken place especially in Japan, then the polar movement curves of the map concerned offer a logical interpretation (KAITERA 1963, p. 344).

A number of palaeoclimatological investigations also support this kind of general continental drift northwards. Statistics collected by GREEN (1961, p. 86) on the position of warm arid regions during 500 million years show that on an average a climatic belt of this kind has moved equatorwards during geological time at a mean rate of five degrees of latitude each 100 million years or 0.5 cm per year. The statistics are significant at the 0.1 per cent level. This belt has always lain roughly parallel to the earth's present equator. This may also be interpreted as a result of a corresponding general continental drift northwards. The parallelism of zones with the present equator implies that the movement of the poles in relation to this belt has been slight at this time. Other investigators have published observations consistent with the above (SCHWARZBACH 1961, p. 186—188; CRAIG 1961, p. 220).

It is clearly apparent, however, that movement of the poles has occurred also in relation to the continents. GREER (1964, p. 1116) has studied the movements of the south pole in relation to Africa, South America and Australia, and those of the north pole in relation to Europe and North America, on the basis of palaeomagnetic observations. He states that, when the severe and widespread Permian remagnetization of Palaeozoic red rocks in Europe and North America is taken into account, the curves for these continents during earlier periods change essentially. By combining in a certain way the curves for polar wanderings, he obtained for instance figure 9, and inferred as follows: The palaeomagnetic south pole drifted across Gondwana-land from a position to the north-west of Africa across Africa to a position off the coast of south-east Africa between the Silurian and Permian epochs. Furthermore he noted that Australia, Africa and South America began to separate and drift into their present positions at about the same time, in the Upper Permian. Before this time the movement of the poles persisted in roughly the same direction for about 200 million years, the average rate of movement being 0.5 degrees per million years.

I have tried to compare the results of the above investigations, assuming that the continents during the Permian were situated relative to the central and lateral ridges as outlined in this paper. Some observations conflict to small extent and one must assume more torque to have taken place in the position of the continents in relation to the longitudes than I have earlier supposed on the basis of the map presented by DOELL and COX. But roughly the above mentioned investigations show the same features in regard to the development of the earth's

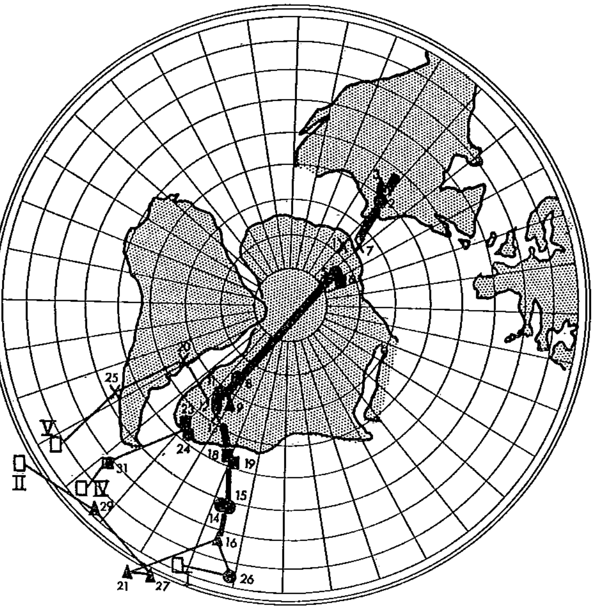

Fig. 9. Palaeogeographic reconstruction obtained by fitting the Upper Palaeozoic palaeomagnetic south poles to the single curve marked by a thick line. The order in which the present continents broke away from the large landmass is indicated by the order in which the indivitual polar wandering curves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

relief and to the shape and position of the continents. These features are in good agreement with the sea pressure hypothesis.

Munk and MacDonald (1960) have made a study of various factors and conditions that might possibly have resulted in the dislocation of the rotation axis of the earth. Having regard to the distribution of continents and seas and assuming the equatorial bulge to be anelastic, the final position of the pole is the one that places the continents as well as possible on top of the equatorial bulge. The orientation of the principal continental axis has been computed by Milankowitsch, Kuiper and Munk, and the position of the north pole has been considered to be in the vicinity of the Hawaiian Islands almost as far from the present pole as it can get. In fact, the pole corresponding to a minimum moment of inertia is near Archangel. If the moment of inertia is greater in continental than in oceanic areas, the north pole should be moving towards the equatorial Pacific. The travel time depends on the anelasticity; it is less than 100,000 years according to the interpretation of BONDI and GOLD of the damping of the Chandler wobble. The fact that the pole is neither in the Pacific nor travelling towards it at this rate poses a dilemma.

MUNK and MACDONALD (1960, p. 279), whose report is quoted in the preceding paragraph, pointed out that, if isostatic balance does not hold precisely but there is uncompensated erosion of continental matter and deposition on the sea floor, then the pole of maximum inertia is at Archangel relatively close to the actual location of the north pole. It appears that 15 m of uncompensated sediments would reverse the balance between the continents and oceans, and then the pole corresponding to a maximum moment of inertia is near Archangel. MILANKOWITSCH has drawn the path of the pole from Hawaii to Archangel through the situation of the present pole on the assumption that this direction of movement is supported by palaeoclimatological evidence.

The amount and influence of erosion and sedimentation, as presented above, support the possibility that there is no exact isostatic balance between continents and oceans. On the basis of the sea pressure hypothesis, the onset of flow in the mantle from marine areas towards the continents is preceded by diminution of the load on the continents due to erosion and a corresponding increase of pressure on the oceans.

Since the location of the poles is dependent upon the location of continents on the earth, it follows that continuous continental drift must be a factor in polar wanderings. The continued increase in sea pressure owing to erosion and sedimentation and the variations of the sea level may thus be physical causes of polar movements. Seeing that the movement of continents and poles are simultaneous, the apparent speed of the movement of the south pole in relation to a certain continent may differ in relation to some other continent. As envisaged above, while Africa and Australia have moved northwards, the south pole has moved in a direction opposite to their movement. However, the general direction of movement of Antarctica seems to have been similar to that of the south pole.

SCHWARZBACH (1961, p. 194—231) states, in dealing with various theories on the causes of the climatic variations possibly responsible for the two most extensive, known ice ages, that none of the numerous hypotheses offer a full solution to the problems. His own view is that climatic development is due in the main to two simultaneous factors: variations in solar radiation and the changing picture of the earth's crust. He considers that especially the climatic variations noted during Gondwana glaciation are not possible unless polar wanderings and continental drift have occurred. Displacement of the south pole across Gondwana-land, as outlined for instance by GREER, may suffice to explain in the main the location close to the present equator of most Carboniferous-Permian moraine deposits indicative of glaciation. At the same time such movements of the poles and continents account for the formation, simultaneously with extensive continental glaciers, of thick tropical coal deposits in other parts of the globe.

Carboniferous-Permian glaciation also provides a possible explanation of the breaking up of Gondwana-land starting at that time and the drifting of adjacent continents far apart. Glaciers several kilometres in thickness, and their melting within a relatively short period, can set up sub-crustal currents which split up continents. In addition, the northward drifting of Asia may have caused torque in the continental sectors, and this has possibly promoted the splitting of Gondwana-land.

The phenomena under discussion are highly complex. 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 (fig. 6). In attempt 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, like these (CHADWICK 1962, p. 223). In these cases it has been overlooked that they may mobilize forces associated with expansion of material to work in the same direction and that there are also other forces, such as the variations of the sea level, accompanying the influence of the sediments as described before.

The viewpoints presented on the mechanism of sea pressure are only very general assumptions made on the basis, not only of the works referred to in this article, but also of much other circumstantial evidence of this type. Though later research is likely to cause adjustments of my assumptions with regard to details, the fact that no changes have been necessary in the original basic assumption of the sea pressure hypothesis, but new viewpoints have continually appeared in behalf of it, has made me convinced that it contains a reality fertile 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.

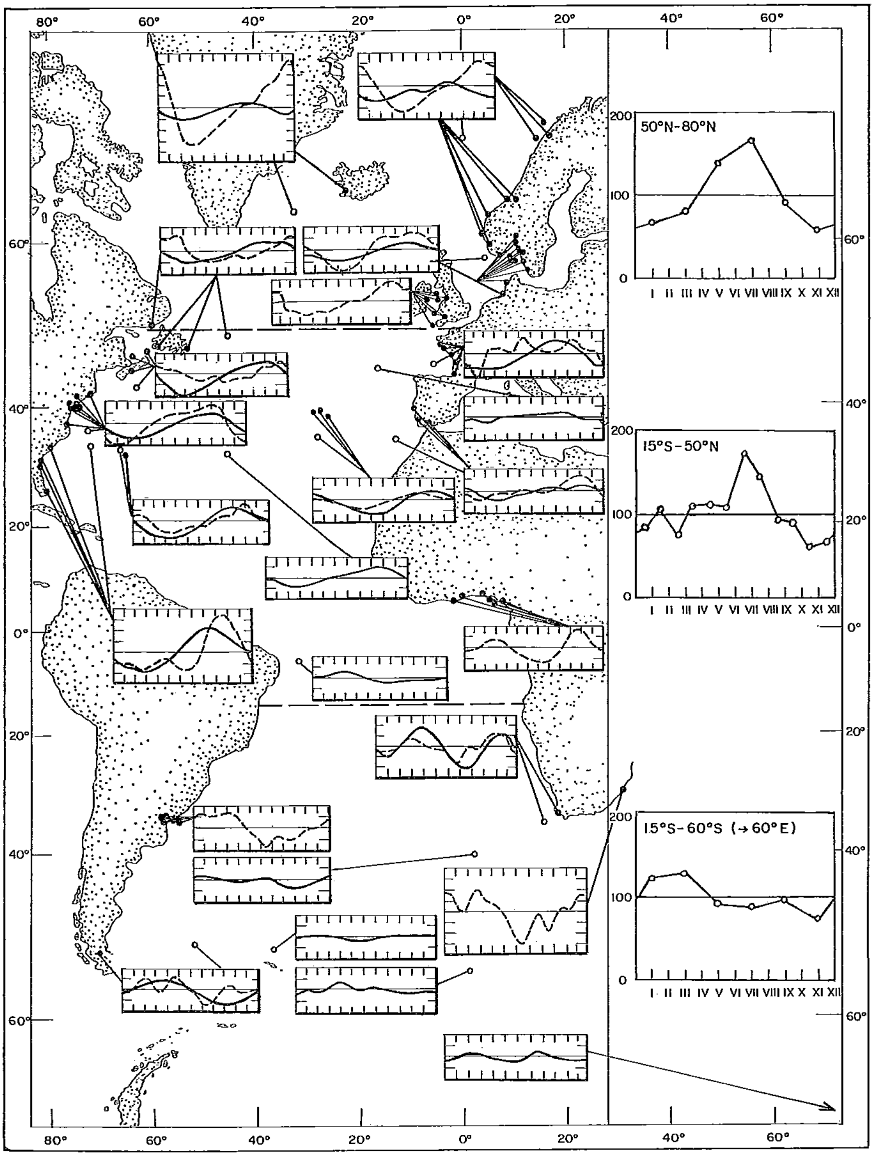

Fig. 10. The seasonal oscillations of the recorded sea level (dashed lines in the diagrams at left) and the steric sea level (continuous lines) in some areas of the Atlantic (the small circles indiacte observation points, the departures from the annual average are represented by the diagrams, one interval being 5 cm of water level) and the relative frequency of earthquakes (the diagrams at right) in different parts of the Mid-Atlantic Ridge.

Postscript. While proofreading the revision sheet of this study, I thought it might be interesting to check whether earthquakes occur more often during high sea level than when sea level is low although it has not been possible to establish any distinct correlation between the tidal cycle and earthquakes (TAMS 1926, p. 58).

I chose the earthquakes observed in the Mid-Atlantic ridge to be the objects of a preliminary study, as the earthquakes on the continents and near them may be the results of processes which are much more complicated than those occurring in the centre of an ocean. I concentrated my study on seasonal fluctuations only. The results are shown in fig. 10. The relative frequency of earthquakes in various parts of the Atlantic has been taken from the Catalogue of Earthquakes 1925—1930, and from the Catalogue of Epicentres in International Seismological Summary 1951—1958 (1955 is missing). Due to the scarceness of the material, the northernmost area (50°N—80°N) has been dealt with in groups of two months (174 earthquakes), the middle area (15°S—50°N) in groups of one month (329 earthquakes), and the southernmost area (15°S—60°S and along the central Atlantic ridge until the 60th longitude) in two-month groups (109 earthquakes). The seasonal oscillations in sea level and the steric sea level oscillations (arising from the seasonal departures in specific volume) have been got from the examinations by J. PATTULLO and others, in 1955. As the picture shows, a annual cycle of earthquake frequency can be observed in all regions. In the Northern Hemisphere, the maximum occurs in the second half of the year: in the Southern Hemisphere the maximum occurs in the first half. Regarding sea level, the maximum in the Northern Hemisphere occurs in the autumn and in the Southern Hemisphere also in autumn but about half year earlier than in the Northern Hemisphere as does the maximum of the earthquakes.

There is reason to point out, that if for instance the convection currents were the main reason for earthquakes observed in the Mid-Atlantic, a phase like this would not exist. The result indicates that the essential cause of earthquakes is some cause dependent on meteorological factors such as the sea pressure, which in this comparison seems to correlate with the frequency of earthquakes especially when one takes into account also the seasonal variations of atmospheric pressure. The maximum of the earthquakes occurs in the Mid-Atlantic ridge when atmospheric pressure is high and sea level is rising, especially in the Northern Hemisphere where more observations are available.

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APPENDIX

THE INVESTIGATING OF THE MAGMA CURRENT CAUSED BY THE SEA PRESSURE AS A PROBLEM OF LEVEL CURRENT OF VISCOUS LIQUID

by

HEIKKI KUTVONEN

Starting out from the differential equations of NAVIER—STOKES, and omitting the terms of inertia (the flow of extremely viscous fluid), and assuming the mass forces to originate exclusively from gravitation, and assuming magma to be uncompressed, we get for the vertical velocity of magma in a Cartesian co-ordinate system, the differential equation

$$\frac{\partial^4 w}{\partial x^4} + 2\,\frac{\partial^4 w}{\partial x^2\,\partial z^2} + \frac{\partial^4 w}{\partial z^4} = 0 \tag{1}$$

For the sake of simplicity we assume the solution to have the form

$$w = \Sigma\, w_n\,(z) \cdot \cos \alpha_n x \tag{2}$$

By substituting this in the first equation, and solving the differential equation obtained, we get an expression for the vertical velocity and hence the horizontal velocity and the stresses. The first terms of the series of the quantities in question are (omitting the index marks):

$$\left\{\begin{aligned}
w &= \cos \alpha x\,[(A + Bz)\,e^{-\alpha z} + (C + D\,z)e^{\alpha z}]\\
u &= \sin \alpha x\,[(A + Bz - B/\alpha)\,e^{-\alpha z} - (C + Dz + D/\alpha)\,e^{\alpha z}]\\
\tau_{xz} &= -\,2\mu\alpha \sin \alpha x\,[(A + Bz - B/\alpha)\,e^{-\alpha z} + (C + Dz + D/\alpha)\,e^{\alpha z}]\\
\sigma_z &= -\,2\mu\alpha \cos \alpha x\,[(A + Bz)e^{-\alpha z} - (C + Dz)\,e^{\alpha z}] - z\gamma\\
\sigma_x &= \quad 2\mu\alpha \cos \alpha x[(A + Bz - 2B/\alpha)\,e^{-\alpha z} - (C + Dz +\\
&\qquad 2D/\alpha)\,e^{\alpha z}] - z\gamma
\end{aligned}\right. \tag{3}$$

If we consider a situation where the crust and mantle consists of two layers with different viscosity constants, the above quantities must have, their own equations in each layer.

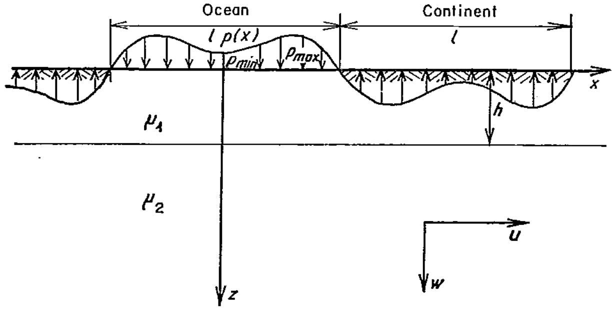

Fig. 1. The co-ordinate system used.

If the upper layer thickness equals h and assuming that the lower layer extends practically to infinity, there will be 4 integration constants for layer one, and 2 for layer two. To determine the integration constants the following boundary conditions are available:

when $z = 0$

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

when $z = h$

$$\begin{cases} w_1 = w_2 \\ u_1 = u_2 \\ \sigma_{z1} = \sigma_{z2} \\ \tau_{xz1} = \tau_{xz2} \end{cases}$$

Assuming that the pressure $p(x)$ has the following form:

$$p(x) = p_1 \cos \frac{\pi x}{l} - p \cos \frac{3\pi x}{l}$$

and, to facilitate comparison, that $p_1 - p_3 = p_0$ (in this examination it is assumed that $p_0 = 20$ kp/cm^2, which corresponds to the pressure of a 200 m layer of water), we obtain the following expressions for the integration constants:

$$\begin{cases} A_1 = \dfrac{p}{2\mu_1\alpha} \dfrac{e^{2\alpha h}\left(1 - 2\alpha h + 2h^2\alpha^2 - \dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h}\right)\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}}{4\alpha^2h^2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - 1 + 2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - \left(\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}\right)^2 e^{4\alpha h}} \\ B_1 = \dfrac{p}{2\mu_1} \dfrac{e^{2\alpha h}\left(1 - \dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - 2\alpha h\right)\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}}{4\alpha^2h^2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - 1 + 2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - \left(\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}\right)^2 e^{4\alpha h}} \\ C_1 = \dfrac{p}{2\mu_1\alpha} \dfrac{\left(1 - \dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{h\alpha h} - 2\alpha h\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - 2\alpha^2h^2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{h\alpha h}\right)}{4\alpha^2h^2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - 1 + 2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - \left(\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}\right)^2 e^{4\alpha h}} \\ D_1 = \dfrac{p}{2\mu_1} \dfrac{\left(-1 + \dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} + 2\alpha h\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h}\right)}{4\alpha^2h^2\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}e^{2\alpha h} - 1 + 2\dfrac{\mu_1+\mu_1}{\mu_1-\mu_2}e^{2\alpha h} - \left(\dfrac{\mu_1+\mu_2}{\mu_1-\mu_2}\right)^2 e^{4\alpha h}} \\ A_2 = \dfrac{2\mu_1}{\mu_1+\mu_3}A_1 \quad ; \quad B_2 = \dfrac{2\mu_1}{\mu_1+\mu_2}B_1 \end{cases}$$

For the first terms of the series $p = p_1$ and $\alpha = \pi/l$. For the other terms $p = -p_3$ and $\alpha = 3\pi/l$.

The calculations have been made using the following values of p_1 and p_3:

p_1	p_3	$p(x)_{\max}/p_0$
1.27 p_0	0.424 p_0	1.41
1.90 »	0.900 »	2.0
3.87 »	2.87 »	5.0
7.12 »	6.12 »	10.0

The first line indicates the values for which (with two terms) $p(x) \approx$ constant $= p_0$.

Example:

$$h = 30\,\text{km},\quad l = 3000\,\text{km},\quad \mu_1 = 10^{23}\text{g/cms},\quad \mu_2 = 10^{21}\text{g/cms}$$

$p \approx$ constant:

$$z = 500\ \text{km}\begin{cases}\tau(1/2) = -10.6\ \text{kg/cm}^2\\ w(0) = 26.2\ \text{cm/yr}\\ u(1/2) = 10.6\ \text{cm/yr}\end{cases}$$

$$z = 700\ \text{km}\begin{cases}\tau(1/2) = -11.0\ \text{kg/cm}^2\\ w(0) = 24.6\ \text{cm/yr}\\ u(1/2) = 11.7\ \text{cm/yr}\end{cases}$$

$p_{\max}/p_0 = 2$

$$z = 300\ \text{km}\begin{cases}\tau(1/2) = -14.9\ \text{kg/cm}^2\\ w(0) = 38.8\ \text{cm/yr}\\ u(1/2) = 16.5\ \text{cm/yr}\end{cases}$$

$$z = 700\ \text{km}\begin{cases}\tau(1/2) = -17.7\ \text{kg/cm}^2\\ w(0) = 36.0\ \text{cm/yr}\\ u(1/2) = 17.9\ \text{cm/yr}\end{cases}$$

$p_{\max}/p_0 = 5$

$$z = 100\ \text{km}\begin{cases}\tau(1/2) = -18.1\ \text{kg/cm}^2\\ w(0) = 71.3\ \text{cm/yr}\\ u(1/2) = 12.6\ \text{cm/yr}\end{cases}$$

$$z = 700\ \text{km}\begin{cases}\tau(1/2) = -41.2\ \text{kg/cm}^2\\ w(0) = 70.2\ \text{cm/yr}\\ u(1/2) = 38.6\ \text{cm/yr}\end{cases}$$

$p_{\max}/p_0 = 10$

$$z = 50\ \text{km}\begin{cases}\tau(1/2) = -17.7\ \text{kg/cm}^2\\ w(0) = 124\ \text{cm/yr}\\ u(1/2) = 11.5\ \text{cm/yr}\end{cases}$$

$$z = 700\ \text{km}\begin{cases}\tau(1/2) = -79.9\ \text{kg/cm}^2\\ w(0) = 127\ \text{cm/yr}\\ u(1/2) = 72.7\ \text{cm/yr}\end{cases}$$

The effect of the dimensions of the sea: If the diameter of the sea is decreased, the depths of effect and velocities will be decreased. The shear stresses increase considerably in the very surface layers. Increasing the sea area increases velocities and depth of effect, decreases shear stresses in surface layers — to a slighter extent also deeper.

The effect of viscosity: If the relation of the viscosity constants remains constant, the velocities will be inversely proportional to the degree of viscosity. The stresses are independent of the viscosity constants. The velocities of current, deeper down, depend little on the viscosity in the surface layer. The velocities of current deeper down are nearly inversely proportional to the viscosity of the lower layer, regardless of the viscosity of the upper layer.

The effect of the thickness of layer: If the layer-thickness (h) is increased, the maximum shear stress of the upper layer will be increased. In the lower layer, the effect of the thickness of the upper layer will be slight.

Closing remark

In solving the problem, time has not been taken into account in any way. In reality, the velocities of current will never achieve a growth of the magnitude indicated by the calculations, because the current flow will start as soon as the shear strength of magma (possibly about 10 kg/cm^2) is exceeded and the disequilibrium of the forces is released.