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THE THERMODYNAMICS OF THE EARTH'S CRUST II

On the Theory of the Origin of Folded Mountains.

BY

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With 7 figures.

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Introduction.

The origin of folded mountains is by most investigators considered as a problem of tectonics; according to my view, however, the orogenesis is as much a problem of regional metamorphism and granitisation. The intimate connection between folded mountain chains on the one hand and dynamothermal metamorphism and granitisation on the other hand has made me try to work out a new theory pertaining to some questions concerning the origin of folded mountain chains. In the following few pages the principal feature of the theory is discussed.

The Different Steps of the Mountain-Making Process.

The evolution of folded mountain chains is a combination of the most varying and interesting geological processes. Mountain chains have their typical tectonics, they have their typical magmatic activity, their characteristic regional metamorphism and granitisation, and last but not least each step of the mountain-making process has its typical geomorphology. These, and many other geological and geophysical

phenomena must be taken into consideration in a general theory of the origin of folded mountains.

Thanks to the studies of the pre-Cambrian formations in the last decennia we know in general the architecture and composition of the folded chains from the deepest sections laid bare in the pre-Cambrian peneplains up to the highest sections of the recent mountains. The studies of the sedimentary facies and the tectonics of older and younger folded mountains have also enabled us to get an understanding of the main feature of the evolution of a folded mountain chain. We know in general the movements and other processes, as, for instance, the metamorphism and the igneous activities which have taken place during the development of mountains. But the causes of these processes, the forces and potentials which must exist in the earth's crust, and drive the whole mountain-making process, are by far not made out. This paper deals with the potentials of a mechanical and a chemical nature existing in the earth's crust during a period of orogenesis.

For this purpose we shall first give a short description of the evolution of a folded mountain chain in accordance with the view of those in authority.¹

The complete evolution of a folded mountain is commonly divided into three epochs, viz.: (1) the *geosyncline period* or the *thalattogenesis* (Kober), (2) the *orogenesis* itself or the period of *tectogenesis*, and (3) the period of *cratogenesis*.

(1) The geosyncline period. (The thalattogenesis). The metamorphic sedimentary rocks found in every real folded mountain of any geological age show that the high mountains consist of the raised and folded floor of the oceans. An ocean depression or a geosyncline seems to be a necessity for the origin of a folded mountain chain. The mountains are born in the geosynclines, as it is often said. This is a fact which is definitely ascertained by the classic works of Dana, Haug, Schuchert and others.²

¹ See the references in H. Cloos, "Einführung in die Geologie". Berlin 1936, pp. 456—458.

² J. D. Dana: "On Some Results on the Earth's Contraction from Cooling". Am. J. Sci. Vol. 5. 1873, p. 430. E. Haug: "Traité d. Géologie". 1908—1911. Vol. 11. Ch. Schuchert: "Sites and Nature of the North American Geosynclines." Bull. Geol. Soc. Am. Vol. 34, p. 151.

The facies study of the sediments of the folded chains indicates that most of the geosynclines are no primary features of the earth's crust, but that they are depressed continents, while other mountains perhaps are raised ocean basins which may have existed from the beginning of the solid crust.

The geosynclinal period is characterized by basic plutonic and sub-marine volcanic activity.

(2) The orogenesis. (The period of tectogenesis.) The period of orogenesis which follows the geosyncline period is characterized by a horizontal stowing of the basement, and of the sediments and the effusives in the geosyncline. The continents around the geosyncline move towards each other. During this movement the sediments and lavas in the geosyncline are folded, over-folded, and over-thrust. Also the rocks of the old basements are foliated and stowed together. The whole process gives one the impression that the earth's crust beneath the geosyncline is plastic, while the continental blocks are hard, brittle, and unplastic. However, in my opinion, the yielding of the geosyncline and the resistance of the continents are not due to any difference in the physical properties of the rocks of the geosyncline and those of the continents; but it is the forces which do not act to the same degree in the two places that make the difference. *The horizontal stress which causes the compression of the crust only acts in the geosyncline region, and does not effect the continental blocks.*

The regional metamorphism and the granitisation of the folded chain are most intensive during the tectogenesis, but it is reasonable to assume that the metamorphism extends into the cratogenic period as well as backward into the geosyncline period.

The metamorphism is characterized by a continuous increase of the P, T values from the rigid frontiers towards the plastically folded central zones of the mountain chains. In the most intensively metamorphosed parts the granitisation occurs with its diffusion of the dispersed granitic substance into the folded rocks. Granite pegmatites are usually encountered in the basic rocks of the granitized areas, while the quartz veins and alpine veins exist in the low grade metamorphic areas.

Considering the cratogenic elevation of the central parts of the folded chain after the period of most intensive metamorphism (the tectogenesis), and the greater denudation of the central zones than

along the frontiers, the horizontal increment of the P, T-values during the metamorphism is perhaps only a result of the vertical P, T-gradient.

The characteristic plutonic activity of the orogenesis or tectogenesis is granitic and granodioritic. More or less conformable batholiths of these rocks appear in the central zones of the folded chains. There is an apparent connection in space and time between the granites on the one hand, and the metamorphism and granitisation on the other; the metamorphism and granitisation increase towards the granitic masses.

(3) The period of cratogenesis. During this third and finishing period the whole folded chain is elevated *en bloc* thousands of meters, giving the geographic mountains with their peak, ridges, and high plateaus.

The cratogenic elevation probably takes place at the same time as the orogenic horizontal compression, but the cratogenesis survives the orogenesis, and occurs as the final process which carries the evolution of the folded mountain chains to completion.

The so-called post-kinematic granites, and the last step of the metamorphism and granitisation probably occur in this period. Acid volcanic activity is perhaps also bound to the period of cratogenesis.

To summarize: During the evolution of the folded chain a centripetal sinking movement first occurs (the thalattogenesis); this is followed by horizontal movements near the surface of the earth (the orogenesis), and, finally, a vertical elevating movement raises the folded crust (the cratogenesis). The sinking is accompanied by basic igneous activity; the horizontal stowing and the elevation are accompanied by acid granitic magmatic and metasomatic activity.

The Geological and Physico-Chemical Principles Underlying the Theory.

The knowledge of the isostatic conditions of the different steps of the mountain-making process is of fundamental significance for the following theory. Our knowledge of the evolution of mountain chains is a result of geological studies of recent and older folded chains. But such studies cannot tell anything of the isostatic conditions of the two earliest periods of the mountain-making process:

the geosyncline period and the period of orogenesis. For the isostatic properties are investigated directly by gravimetric measurements.

The direct gravimetric study of an existing geosyncline will be of the greatest interest for the understanding of the origin of folded mountains. It would seem reasonable that the recent ocean basins represent geosynclines of future mountains. If so be the case the geosynclines, which represent the first stage of the mountain evolution, as well as the last step — the recent geographic mountains — are in isostatic equilibrium. Or more exactly, the geosyncline (ocean) shows a small mass surplus while the high mountain shows a small mass deficiency.³

The fact that the earth's crust is in isostatic equilibrium regardless of it being occupied by geosyncline depressions or high mountains demands a special interrelation between the forces which drive the mountain-making process and the average specific gravity of the part of the crust which is included in the process. With reference to the crust above the level of isostatic compensation, the average specific gravities of the rocks beneath the geosyncline depression are, as we know, greater than the specific gravities of the rocks in the continents or the mountains. The rocks beneath the high mountains are lighter than the average continent rocks.

It is the horizontal compression — the orogenesis itself — which is the most conspicuous process during the birth of folded mountains. The horizontal forces are therefore commonly over-valued and regarded as primary, while the vertical movements and the variation of the specific gravity of the crust are looked upon as secondary phenomena. The present theory, however, is based on the hypothesis that the variation of the average specific gravity of the earth's crust is the primary phenomenon; *the vertical depression is caused by an increase of the average specific gravity of the crust. The compression and folding movements are secondary, and result from a plastic flowing together of the existing depression. The cratogenic elevation of the folded crust results from a decrement of the average specific gravity of the rocks.*

A probable reason for the increment of the average specific gravity of the sinking geosyncline, is a mixing of the light sial sphere

³ E. Tams: "Grundzüge der physikalischen Verhältnisse der festen Erde." I. Berlin 1932, pp. 147—181.

with the heavy lower sima sphere below the depression (simatisation of sial). But such a heavy sunken area is not thermodynamically stable during geological periods in spite of the isostatic compensation of it and in spite of the crystalline state of the sial and sima. Because of the metamorphic plasticity of the solid rocks the basin must flow together as would any other depression in a plastic mass. During this flowing together of the geosynclines, the crust and its sediments are folded and elevated in a manner which corresponds to the process of orogenesis and cratogenesis as summarized above.

We shall now make it reasonable that the mountain chains of the earth are formed in this way; we shall furthermore prove by means of physico-chemical laws in connection with our view of the geology of the earth that any geosyncline-like depression in the earth's crust is unstable and must generate phenomena similar to the upfolding of mountain chains.

Before we turn to the discussion of the theory we shall briefly consider the architecture and composition of the outer layers of the earth and the most significant physico-chemical laws of the solid crystalline rocks.

It is generally believed that the earth's crust consists of an external granitic shell of about 20—40 km thickness, (the sial), and an internal basaltic or gabbroic layer (the sima).⁴ (As we shall see later the "crust" of the earth is a relative, time-dependent conception. For long existing strain the crust is plastic up to the highest levels; for short existing strain the plastic flow only takes place in the depth, and the upper parts are brittle. The longer the strain exists, the higher up in the solid crust does plastic flow develop.)

The granitic shell (sial) is crystalline throughout. The upper parts of the gabbroic shell (sima) are also crystalline; it is, however, possible but not very reasonable that the deeper sections of the gabbroic sphere are molten or vitreous. It is the level of isostatic compensation which seems to exist in a definite depth (about 100 km), and the universal basaltic eruptions (the plateau basalts) which have created the conception of a molten or vitreous substratum of basaltic composition. But both these phenomena can also occur when the earth is crystalline below the level of the isostatic compensation. An isostatic compensation is able to take place in crystalline state due to

⁴ E. Tams. *op. cit.*, pp. 58—59.

the metamorphic plasticity of the rocks in the depth. (Gravimetric observations show that the level of the isostatic compensation is not constant, but ranges between about 120 and 60 km.⁵ This is in agreement with the theory that the isostatic compensation takes place in crystalline rocks; in that case the level of the compensation is dependent on the length of the time in which the isostatic tension have existed. The longer the duration of gravimetric and isostatic instabilities, the higher the level of compensation. The basaltic igneous activity can be explained by a remelting of the crystalline rocks caused, for instance, by heat liberated during adjustments of equilibria in the interior of the earth.)

We must remember that geophysical data as for instance the penetrability of the earth down to 2900 km for transverse earthquake waves, the deep-seated foci of earth-quakes,⁶ and the assumption of an eclogitic ⁷ shell below the basaltic shell indicate a crystalline state of the earth down to great depths. (The chemical compositions of eclogite and gabbro are identical; a conception of an eclogitic shell below the gabbroic shell is therefore absurd if the earth is liquid or vitreous at these levels.)

The external parts of the granitic shell is rather heterogeneous including the most varied rocks of sedimentary and magmatic origin. Where the deeper sections of the earth are laid bare, however, we find a more homogeneous granitic rock (the pre-Cambrian peneplains).

The heavy gabbroic shell naturally enough does not crop out in the continents, and it therefore escapes direct observation.

One of the most important physico-chemical properties of the rock is, for our theory, the peculiar plasticity in crystalline state under high pressure and long existing stress. The great pressure existing in the depth of the earth, and the long time the reactions here have at their disposal during geological periods give the crystalline state properties in common with both solids and liquids. For long existing stress the crystalline matter flows like melts, for short existing stress the crystalline matter is rigid and brittle. However, it is important to notice that the minerals of the flowing crystalline rocks cannot

⁵ E. Tams op. cit., pp. 132—134.

⁶ Ch. E. Stehn: "Vulkanische Verchijnselen en Ardbevingen — — —" *Naturk. Tijdschrift v. Nederl. Indie*. Batavia 1935, p. 22.

⁷ V. M. Goldschmidt: "Der Stoffwechsel der Erde." *Vid.-selsk. skr. Mat.-Nat. kl.* 1922, nr. 11.

be mixed homogeneously together like most melts, in spite of the liquid-like flow of the rock minerals.

The metamorphic plasticity is to a great degree of a chemical nature and has connection with migrations of dispersed particles outside and inside the space lattices of the minerals. In addition the plasticity is due to mechanical translations in the lattice, but for our task it is of the greatest significance that physico-chemical processes such as aggregate transitions and diffusion also take place during the plastic deformations of the crystalline rocks.

Another significant property of the crystalline rocks in great depth where the pressure is great and the temperature high, is their great permeability for dispersed particles. The investigations of metamorphic areas prove that especially the dispersed granitic substance is able to penetrate the rock complexes and travel long distances through the solid rocks. The much higher mobility of granitic minerals than of gabbroic under regional-metamorphic conditions is probably due to greater chemical activities of the granitic minerals than of the gabbroic minerals. Quartz, potash feldspar, and acid plagioclase are more mobile than are pyroxene, hornblende, and basic plagioclase. The dispersed particles which penetrate the solid rocks during the metamorphism are therefore enriched in the atoms of the granites, and by consolidation, granitic minerals and rocks effloresce (petroblastesis).⁸

Along with these empirically found properties of rocks we have to consider some theoretically derived properties of the crystalline minerals. Of fundamental importance for our view is that the vapor tension, or more generally the chemical activity of every mineral, increases exponentially with the external pressure.⁹ This causes an increment of the concentration of the dispersed particles at places of high external pressure, and a decrement of the concentration at places of low external pressure. It is further worth while noticing that the chemical activity of the light minerals increases more rapidly with pressure than does the activity of heavy minerals.

Generally, the last explained properties will result in a dispersion of minerals at high pressure, a migration of the dispersed particles inside and outside the lattice towards low pressure, and a consolidation of

⁸ See H. Ramberg. N. G. T. Vol. 24, pp. 98—111.

⁹ H. Ramberg. Vid.-Akad. Avhandlingar. I. Mat.-Nat. Kl. No. 3. 1944.

the minerals here. In other words, there exists a chemical potential between phases of different external pressure at constant temperature. This potential causes a displacement of crystalline matter by diffusion from high to low pressure in a similar manner as the plastic substances are displaced by mechanical processes. (This does not hold good for the vertical pressure gradient in the earth or any other planet; the minerals will not migrate from low levels where the pressure is high to high levels when the pressure is low if the material between the levels is homogeneous (a monomineralic rock) and the temperature is constant.)

Because of the increase of the chemical activity of substances with the temperature, crystalline matter will be transported by dispersion, migration, and consolidation from high temperature to low temperature. A temperature gradient existing in the opposite direction of a pressure gradient in rocks can therefore compensate for the effect of the pressure gradient, and prohibit the migration.

The effect of the pressure upon the chemical activity of minerals generally causes an increment of the rate of chemical reactions with pressure. The metamorphic plasticity which is mostly of a chemical nature must accordingly also increase with the pressure.

A result of the above mentioned relations is that there exist chemical forces which try to arrange the different minerals in homogeneous concentric spheres after their specific gravities, the lighter above, the heavier below in the gravitational field of the earth. Thus these chemical potentials act in the same direction as do the mechanical forces in the gravitational field of the earth.

A heavy rock lying above a light one thus represents an unstable system mechanically as well as chemically. If the rate of chemical reactions is above zero, the rocks will change places by dispersion, migration, and consolidation, until the chemical as well as the mechanical potentials become least possible.¹⁰

The fact that the deep oceans and the continents with their mountain ranges are in isostatic equilibrium is usually explained by an anticline in the sima beneath the oceans, and a syncline in the sima beneath the mountains. Such an isostatically compensated system is stable only if the rocks above the level of isostatic compensation are

¹⁰ H. Ramberg loc. cit.

completely unplastic, and if the rate of the chemical reactions is equal to zero, i. e. if the equilibria are "frozen out". But, according to the study of metamorphism the rate of reaction of the solid rocks in the crust does not equal zero. The light granites of the continents therefore must flow and migrate over the basaltic shell of the oceans until the boundary between sial and sima has become a gravimetric niveau level, and thus the sial has attained constant thickness. And this flowing together of the ocean basins is identical with the commonly known substructure flow during the orogenesis. (Figs. 1—7, pp. 321—323.)

It is also possible that the heavy ocean basin does not represent an anticline in the sima shell; but that the sima and sial may be mixed together to a relatively homogeneous rock of medium specific gravity in the geosyncline basement. Such a rock consists of the heavy basic minerals: plagioclase and pyroxene; and the light acid minerals potash feldspar, albite, and quartz. In that case the region is unstable too; having long enough time at disposal it must split up through metamorphic differentiation into heavy basic rocks and light acid rocks, and the same processes as described above will take place.

The isostatically compensated basins may also be regarded as heterogeneous mixtures of the sial and sima in the upper part of the crust. The granitic shell may be intersected by sills, dikes, and laccoliths of basic rocks, and thick layers of basalt may rest on the surface of the sial. Such structures are certainly also unstable and must give birth to phenomena identical with those of the orogenesis and the cratogenesis as the stable thermodynamic equilibria are being developed.

Some of the basins from which the chains have raised may have existed as unstable regions from the beginning of the earth's solid crust. But other geosynclines may have subsided later. During this subsidence of the geosynclines the isostatically compensated structure must have appeared with its concomitants: the upwelling of the sima or the mixing of the sima and sial. Since the orogenesis — the development of the stable equilibrium in the geosyncline — takes place by means of the slow regional metamorphic processes, the origin of the unstable geosyncline must be caused by quicker geological processes. The process which creates an instability cannot be as slow as the process which causes the adjustment of the same instability if both reactions take place at the same time.

In geology the quick, violent magmatic phenomena stand in opposition to the slow phlegmatic regional metamorphic phenomena. This is also the case in the development of mountains; *quick igneous processes are supposed to cause the instability of the ocean basin (geosyncline), and the slow regional metamorphic processes again establish the equilibria during the orogenesis.*

The intimate relation between oceans and basaltic volcanism is a conspicuous phenomenon in the earth today. The metamorphic basic lavas of older folded chains also testify to a common basic volcanic activity in earlier ocean basins or geosynclines. Thus the sinking of the Scandic in connection with basaltic eruptions took place about 50 million years ago. The depression of parts of the Indic is usually seen in relation to the eruption of the plateau basalts of Deccan.

The absence of such enormous layers of basalt which are necessary for the thalattogenic depression of the earth's surface thousands of meters below sea level is obviously no indication against the theory. Such a large-sized basaltic body resting on the earth's surface is necessarily not stable; due to isostatic compensation it will soon founder below sea level and avoid observation.

Description of the Theory.

Caused by unknown forces a region of the granitic shell is afflicted by an intensive basic igneous activity. Intrusive and extrusive bodies appear in and on the sialic crust. Gradually the molten sima masses solidify and increase the average specific gravity of the area (fig. 2). According to the empirical laws of isostasy the region must founder; the region is transgressed by the sea, the sediments begin to settle, and the weight of the sediments makes the crust sink farther down (fig. 3).

Now it is believed, as explained at the outset, that the isostatic movements take place in crystalline state. Beneath the sinking area the solid rocks must flow away from the depression towards the surrounding continents (fig. 3). We have seen that the plasticity increases rapidly downwards, i. e. for equal stress the plastic flow is quicker in deeper levels than in higher. The plastic movements which cause the sinking of the geosyncline therefore begin in great depths. The crust above these depths behaves as a rigid body. Suppose that the compensation at first takes place somewhere in the sima shell,

then the surface between sima and sial must be depressed to a syncline (fig. 3).

As to the conditions in the depths before the depression of the geosyncline took place, we find that the pressure at a given level under the future geosyncline is greater than under the continents.

Consequently there exist pressure gradients along the gravimetric niveau surfaces, pointing from the future geosyncline towards the continents. Such pressure gradients along gravimetric niveau surfaces are certainly not stable; they will cause movements in the substratum away from the future depression towards the continents. These movements are both plastic mechanical flow in the crystalline rocks as well as chemical dispersion, migration, and consolidation. Caused by the movements thus the sima-intruded sial block will founder until the isostatic equilibrium is attained (fig. 3).

But the crystalline rocks are also metamorphically plastic in higher levels if the reactions have long enough time at their disposal. That is to say, the plastic reactions of chemical and mechanical nature are accomplished in gradually higher levels as time goes on. The rigid block which sank down into the plastic substratum below the level of isostatic compensation, itself begins successively to react in a plastic manner. We realize that below this level of isostatic compensation the different rocks are arranged in concentric shells, and that the thermodynamic equilibria are well under way to complete readjustment. And this level moves gradually towards the earth's surface. If the sima is a homogeneous mass nothing will happen until the level of compensation reaches the lower parts of the depressed sial shell. Here the attainment of equilibrium causes the granitic masses to flow from the depression towards the continent, and the gabbroic substratum will flow towards the depression and fill this from below (fig. 4). The boundary surface between sima and sial will become a gravimetric niveau surface as equilibrium is established. As time goes on, however, reactions higher up in the sial shell will help to attain equilibrium, and thus the lowest gabbroic bodies in the sial are reached by the upward moving level of complete equilibria adjustment. The metamorphic plasticity begins to work at these high levels, and the heavy basic bodies begin to sink down through the light granitic shell (fig. 5).

The weight of the heavy gabbroic masses increases the chemical activities of the granitic minerals along the lowest boundaries of the gabbros, and the dispersed granitic substances diffuse upwards pene-

trating the gabbros inside and outside the minerals, and consolidate in the sial above the gabbros and in greater openings in the gabbroic masses where the pressure is low (pegmatites). At the same time the sial flows in a plastic manner around the basic masses, the gabbros making their way down to their stable niveau — the basic substratum. Thus the gabbros lying in successively higher levels gradually sink down through the granitic shell; and the granites from the surroundings occupy the spaces of the sinking gabbroic bodies.

The thick basalt layer covering the granitic shell in the geosyncline has now been covered by relatively thick layers of sediments. (Sediment series of 10—15 km thickness are not unusual in folded chains, as we know.) Under this heavy load the pressure is relatively great and it is reasonable to assume that the reaction in the crystalline state after a sufficiently long time also will take place here.

The granitic rocks below the basalt layer begin to flow under metamorphic-plastic conditions. Dispersed granitic particles migrate upwards through the basic layer and consolidate in the sediments above where the pressure is low (granitisation). At the places where the pressure is lowest — in fissures and other openings — the dispersed granitic phase is highly supersaturated and it will crystallize, forming granite pegmatites.

The basalt layer sinks through the sial, and the orogenesis itself takes place in its most typical manner (fig. 6).

The conditions in the sediments and the continents in one and the same depth (niveau surface) are characterized by the fact that the pressure is lower in the sediments than in the continents. The crystalline plastic flow which now begins to work in these high levels also, causes therefore the granites of the continents to flow towards the geosyncline below the sediments, between these and the sinking basaltic layer. This flowing together of the geosyncline is identical to the substructure flow of the orogenesis; it must cause a horizontal compression of the outermost rigid parts of the crust, and of the sediments in the geosyncline.

Diapiric granites may appear during the crystalline flow: the solid granites which flow more or less horizontally below the sediments are able to press themselves upward through the sediments at places where the pressure is low.

The pressure potential existing between the substructure below the continents and below the geosyncline will not only cause a

mechanical flow of the sial; also a diffusion of the materials from the continents towards the sediments takes place. Because of the difference in pressure between continents and geosyncline in the same niveau the chemical activity of the granitic minerals below the continents is high, below the sediments low. Accordingly the granitic "ichor" will form in the sial of the continents, migrate slowly towards the oceanic depression, and consolidate there. Also in that way granites of apparently magmatic origin may appear. By a slow gradual accumulation of quartz, and sodium and potash feldspar in the sediments, greater bodies of granite may eventually occur. By this growing of granites, the surrounding sediments may be folded and upset — tectonical phenomena which surely are of secondary importance in relation to the flowing together of the geosynclinal depression.

This is a simple and natural explanation of the process of granitisation. The granitisation is nothing but a contact metasomatism of regional dimensions occurring around the crystalline granitic shell of the earth's crust. (The granitic "ichor" is not a separate liquid phase penetrating the rocks. It is only those atoms of the solid minerals (and solutions) which possess so great kinetic energy that they are able to jump from point to point inside and outside the lattice.)

It is thus an incontrovertible fact that there exist forces in the crust which will initiate and uphold a plastical flowing together of every oceanic depression, resulting in orogenic movements and typical granitisation of the folding chains. The mountain chains with their characteristic granitisation are the visible testimonies of the adequacy of the existing forces — the chemical equilibria in the crust are not "frozen out" and the rate of reaction is not equal to zero.

We have now explained the depression of a geosyncline in the crust, the orogenesis with its substructure flow and stowing of the geosyncline, and the granitisation phenomena. The regional metamorphism and the cratogenic elevation of the folded area — phenomena which are typical for the further evolution of the folded chain — also demands an explanation in harmony with the theory.

The pressure increase during the metamorphism may be explained by the vertical pressure gradient of the earth and the compression pressure from the continent blocks. The increase of temperature during the metamorphism of the folded chain, however, cannot be explained exclusively by the temperature gradient of the earth. Heat must be brought into the geosyncline from without. The most probable explan-

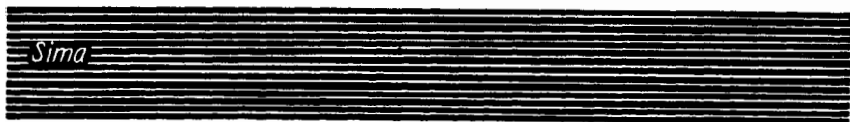
Sial

Fig. 1. Ideal gravimetric and isostatic equilibrium in the earth's crust. The light sial is arranged in a concentric shell above the heavy sima.

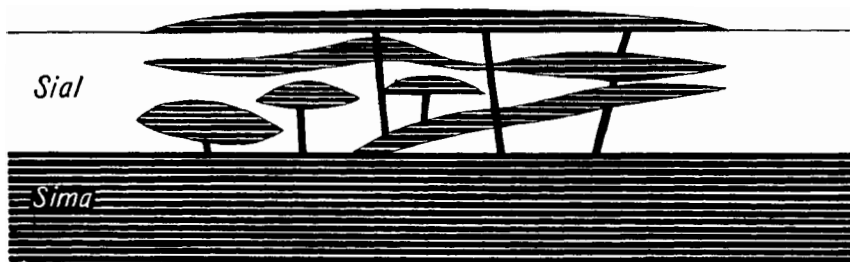


Fig. 2. The ideal gravimetric and isostatic equilibrium is disturbed by intrusion and extrusion of molten sima into the sial shell, and on the earth's surface. The gravimetric equilibrium is disturbed since a heavy gabbroic layer exists above the light granitic shell in the gravitational field, and since heavy gabbros and light granites are heterogeneously mixed in the sial shell. Isostatic equilibrium does not exist since the weight of the superincumbent load at a given level is greater below the disturbed area than below the unaffected surroundings.

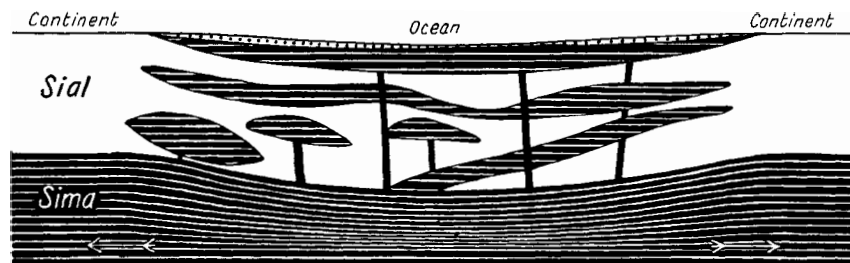


Fig. 3. The isostatic equilibrium is well on the way to complete attainment due to plastic flow (of chemical and mechanical nature) below the level of isostatic compensation in the sima substratum. Still the gravimetric instability exists (see fig. 2).

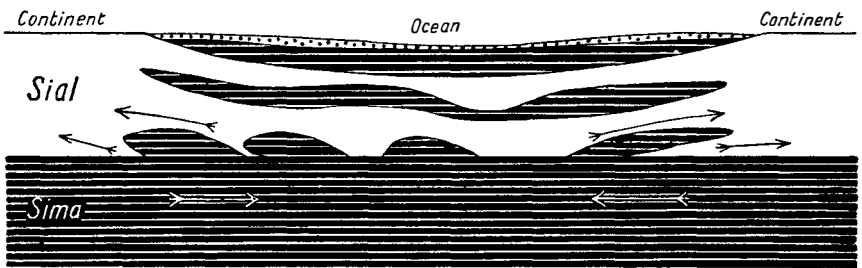


Fig. 4. The level of isostatic compensation and of complete thermodynamic equilibrium (p. 318) has reached the lowest parts of the sial shell. The sima flows towards the depression, and the lowest sial mass flows away from the depression towards the continents (the arrows on fig. 4). Some of the gabbros lying in the lowest parts of sial have sunken down in the sima.

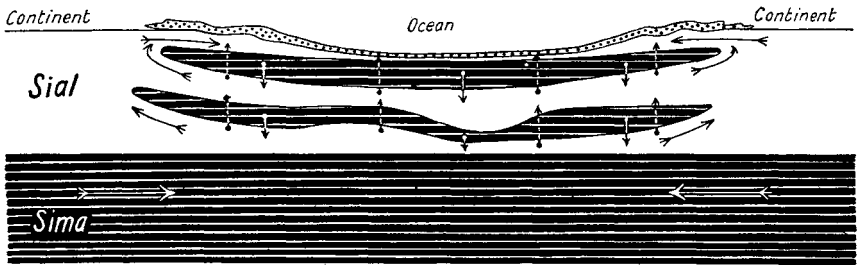


Fig. 5. The reactions take now place to a considerable amount at higher levels in the sial. The gabbro masses which lay in the deepest sections of the sial have already reached their stable niveau — the sima substratum. The gabbros and basalts lying in higher levels sink down through the solid sial due to migration of dispersed granitic matter upward through the gabbros (the stippled arrows), and plastic flow of sial around the gabbros and basalt layer (the solid arrows). The ocean begins slowly to flow together in a plastic manner.

ation is that the heat causing the metamorphism is brought into the sediments with the granitic "ichor". But this is not caused by the cooling of a superheated "ichor"; *rather it seems to be due to the heat of crystallization liberated during the consolidation of the granitic "ichor" in the sediments.* (Consolidation of the migrating dispersed atoms of the minerals.) During this liberation of heat the *temperature of the sediments increases and causes the regional metamorphism.* The heat liberated may also be great enough to melt parts of the sial giving paligenic magmas and acid volcanism. Thus the heat can be

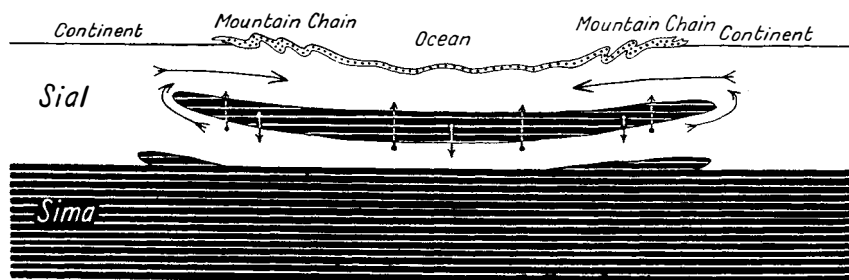


Fig. 6. The reaction even in the highest parts of the crust has now had sufficiently long time to effect great movements and transport of matter. The thick basalt layer which rested on the ocean bottom in the previous periods will now sink down through the solid sial. The dispersed granitic substances which migrate upward through the basalt layer cause a granitisation of the geosynclinal sediments. The granitic masses flow and migrate towards the geosyncline, from the continents. During this flowing together of the geosyncline, the sediments and their substratum are folded, and the folded mountains "creep" up from the geosyncline along the coasts.

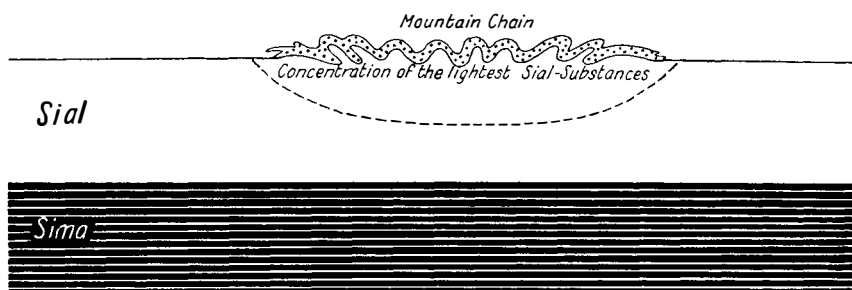


Fig. 7. All the sima masses in the sial have now sunken down to the basic substratum. The geosyncline is completely flown together, the sediments and their floor are folded and the folded and metamorphosed geosyncline is raised above the surface of the continent blocks because of an enrichment of the lightest sialic substances in the folded chain during the granitisation. After a complete denudation of the mountain, the complete isostatic, gravimetric, and thermodynamic equilibrium is again attained as is shown in fig. 1.

brought from places of low temperature (the continents) to places of high temperature (the geosynclines). The sial of the continents is chilled due to the endothermic dispersion of the minerals, the sediments of the geosyncline are heated due to the exothermic process of crystallization. Such a displacement of heat from low to high tempe-

rature demands the liberation of energy which occurs when the sial masses are brought from the high pressure under the continents to the low pressure underneath the geosyncline, and also when the heavy sima masses in the sial sink down to their stable level, viz.: the basaltic shell.

According to this theory we cannot agree with those who demand a root of sial in the sima below a mountain chain. Such a root is not stable, but will soon flow in crystalline state until the depression in the sima is neutralized.

To explain the fact that the mountains which reach thousands of metres above sea level are isostatically compensated, we must therefore assume that the sial masses below the mountains are lighter than the average sial in the continents (fig. 7). In conformity with this assumption stands the low specific gravity of most sediments — the rocks which are assembled in the mountains — as compared with the densities of the “magmatic” rocks of the continents. But the light sediments only occupy the outermost parts of the crust and cannot alone explain the elevation of mountains; the basement rocks below the mountains must also be lighter than the continents. Such light sial masses below the mountains are also in very good agreement with the theory of granitisation explained previously. We must remember that the light granitic minerals are the most mobile minerals according to all petrological experiences, and that the increment of the chemical activity with pressure is greater for light minerals than for heavy ones (see p. 314). That means that the elements of light minerals are selected during the migration from the continents towards the geosyncline and the folded chain. *The lightest minerals are concentrated in the mountain chain by the process of granitisation during the orogenesis and the cratogenesis.* In that way the folded region must rise above the average level of the continents in accordance with the laws of isostasy.¹¹

¹¹ In order to place the considerations here published in the right relation to the interesting views of v. Bemmelen see for instance: *Geologische Rundschau*, Vol. 26, 1935, pp. 199—267.

SUMMARY

(1) The ideal thermodynamic, gravimetrical, and isostatic equilibrium is attained when the light granitic minerals are arranged in a concentric shell above the heavy basic minerals in the earth's crust (fig. 1).

(2) Caused by unknown forces this equilibrium is disturbed by intrusion and extrusion of basaltic magma into the granitic shell, and on the earth's surface (fig. 2).

(3) As the first response on this disturbance of the equilibrium, the area founders due to plastic movements in relatively great depth where the chemical migration processes are rapid (below the level of isostatic compensation) (fig. 3).

(4) As time goes on, however, the slow reactions in gradually higher levels attain geological importance, and the solid sima masses sink down through the solid sial, successively reaching their stable level — the sima substratum. The sinking of the gabbros and basalts through the solid sial is effected by migration of granitic atoms (K, Al, Si, Na) upward through the gabbros inside and outside the mineral lattices; and by mechanical and chemical plastic flow of the granite around the gabbro masses (fig. 4).

(5) In sufficiently long time after the disturbance of the ideal equilibrium (point (1)) and after the depression of the geosyncline (point (2)), the slow chemical reactions cause plastic flow and migration in solid state even in the highest parts of the crust. The floor of the geosyncline, and the sediments get plastic, and the geosynclinal depression flows together as every depression in any plastic mass. This process is the real orogenesis or the tectogenesis (figs. 5 and 6).

(6) The lightest granitic minerals (potash feldspar, quartz, albite, and muscovite) have the greatest chemical activities or vapor tensions, and the vapor tensions of these light minerals will increase more with a given increment of the external pressure than do the vapor tensions of the basic minerals. During the plastic flow and the chemical migration of matter into the geosyncline from the surrounding continents, the light granitic minerals are therefore selected. The lightest minerals are accordingly enriched in the floor and the sediments of the geosyncline. Because of this selecting process the substances below the

rising mountains are lighter than the substances in the continents, and the folded chains must be elevated above the continents (fig. 7).

The granitisation of the sediments and of the floor of the geosyncline is caused by the consolidation of the dispersed granitic minerals in the geosyncline where the activities of the minerals are low due to the low external pressure here, and due to the chemical incompatibility of the granitic minerals and the Al-silicates of the sediments. The dispersed granitic substances are brought into the geosyncline where the chemical activities are low from the continents where the chemical activities are high. The heat of crystallization which is liberated during the granitisation will create an increment of the temperature in the geosyncline, and accordingly a regional metamorphism. If the increase of temperature is great enough, palingenic granitic magmas may appear in this way.

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