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DEEP SOURCES OF ENDOGENIC REGIMES ON THE CONTINENTS

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In some of his earlier publications the present writer, in developing the classic concepts of tectonomagmatic zones and epochs, proposed a classification of the endogenic regimes on the continents, among which he distinguished five classes and thirteen individual regimes [5,6,7]. It is shown here that the distinctive properties of these endogenic regimes are associated with specific thermal conditions in the tectonosphere. On this basis, quiescent and thermally activated regimes are identified. This article will further discuss the connection between endogenic regimes and the geothermal conditions within the tectonosphere.

In the publications mentioned above, the thermally activated regimes were considered to be those in which magmas were melted out from the earth's mantle, and the quiescent regimes those in which this did not occur. This major division, however, suffered from the defect that the number of quiescent regimes included, in particular, those in which, although no magmas were melted out from the mantle, processes of high-temperature metamorphism and anatectic granitization nevertheless did develop within the earth's crust. Such conditions are typical, for example, of the inversional stage of orthogeosynclinal regimes.

It now seems to the writer more correct to assign these last conditions also to the activated category, while at the same time distinguishing between mantle-activated and crustal-activated regimes. In this case the eugeosynclinal regime as a whole, including both its stages, will be considered activated, but the localization of its activation differs in its different stages: in the pre-inversional stage the excitation is confined to the upper mantle, and in the inversional stage to the crust. The criterion of mantle excitation, or activation, is the segregation of mantle magmas, and that of crustal activation is high-temperature metamorphism and granitization within the crust.

Inasmuch as what is meant here is thermal activation, the activated mantle* and activated crust may be called "hot," and the quiescent mantle and crust may be called "cold." It must be kept in mind, however, that these terms have different quantitative meanings as applied to the earth's mantle and crust. A "hot" upper mantle is one in which a basaltic magma is melted out and segregated. For this to happen, at the depth of 100 km the temperature must reach at least 1400°C. If the temperature here drops even to only 1300°C the upper mantle will have the characteristics of a "cold" mantle, inasmuch as the melting out of magmas from it will have ceased. Within the crust, on the other hand, high-temperature metamorphism occurs in the temperature interval of 300° to 700°C, and granitization at 600° to 700°C. Thus the "cold" mantle not only may, but generally will be hotter than the "hot" crust. Because of this relativity of the terms "hot" and "cold," they will be used with quotation marks throughout the present article.

Purely theoretically, one can imagine the following combinations of temperature conditions in the tectonosphere:

"cold" mantle—"cold" crust;
"hot" mantle—"cold" crust;
"cold" mantle—"hot" crust; and
"hot" mantle—"hot" crust.

The reality of the first three sets of conditions is obvious: the first corresponds to the platform and parageosynclinal regimes, and also to the regimes of median massifs

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*By mantle, here and throughout this article, is meant the upper mantle.

and continental margins of the Atlantic type; the second set is characteristic of the pre-inversional stage of the eugeosynclinal regime and of the orogenic and rift regimes, when magmas of mantle origin are segregated but there are no signs of high-temperature metamorphism in the crust; and the third set of conditions is confined to the inversional stage of orthogeosynclinal regimes, when high-temperature metamorphism develops within the crust but no mantle magmas are being segregated. As for the last set of conditions, its actual occurrence in nature is not as clearly evident. It may, perhaps, occur in the regime of continental margins of the Pacific type. This last regime will not be dealt with here (like the regime of continental margins of the Atlantic type), inasmuch as it is the author's intention to limit the scope of this article to typical continental regimes. The regimes of the continental margins are more suitably considered separately, together with the regimes of the ocean floors.

Certain aspects of the connection between the endogenic regimes and the geothermal conditions in the upper mantle and crust will be discussed below.

THERMAL CONDITIONS IN UPPER MANTLE AND ENDOGENIC REGIMES

The level at which magmas are segregated out from the mantle is the asthenosphere. Various data indicate that the volume of liquid in it may range from 5% to 25% of the volume of the initial substance. Experimental research has shown that a relationship exists between the composition of the basalts melted out and the ambient pressure, which with some reservations can be directly related to the depth at which the liquid is separated out from the solid substrate. Seismic observations have led to the conclusion that in different regions of the world the asthenosphere has different thicknesses, lies at different depths, and has different effects on the seismic velocities. Such mantle-activated regimes as the orogenic and the rift regimes are accompanied by a thick asthenosphere lying relatively close to the surface, so that it has a greater effect on the seismic-wave velocities than in the case of quiescent platform regimes. More detailed information on this matter has been presented by the writer in other publications [3,6,7]. These facts are recalled here, first, to support the connection between endogenic regimes and the thermal state of the tectonosphere, and second, to indicate that the mantle is unevenly heated: large regional geothermal inhomogeneities exist within it. If, moreover, it is taken into account that endogenic regimes change not only in space, but also with time, this means that the thermal inhomogeneities are likewise unstable in time, as well as variable in space. The possible causes of this instability will be mentioned below.

One result of the melting out of magmas from the mantle is the "initial magmatism" of eugeosynclines. Most of its volume forms the so-called spilitic-keratophyric association of igneous rocks, consisting of "normal" saturated tholeiitic basalts that have undergone spilitization, and the products of their differentiation. According to the current ideas, a special position is occupied by the ultrabasic rocks (Alpinotypic ultrabasites) that occur in combintation with the spilitic-keratophyric association. According to the now current ideas of "plate tectonics," the ultrabasites together with the accompanying basic rocks of the "ophiolitic series" constitute remnants of the oceanic crust torn away and mechanically squeezed up to the surface from the oceanic crust, on which it is thought that eugeosynclines develop.

This view, however, separates the ophiolites proper from all the remaining manifestations of initial mantle magmatism. Yet the remainder of initial magmatism, whatever forms it may take (effusions, sills, dikes, stocks, etc.) is closely linked in age to the formation of the eugeosyncline and to the age of the sedimentary deposits of the lower terrigenous, asidic, or silicic associations filling it. But the ophiolites, according to the concepts of plate tectonics, should be far older, inasmuch as they are fragments of the same substrate on which the eugeosyncline began to form. It can be readily seen that from this standpoint, the occurrence of ultrabasites among the other rocks of initial magmatism is essentially accidental, since even if eugeosynclinal basins were always formed on an oceanic crust, the latter should not necessarily always be squeezed up all the way to the surface in the form of ophiolite protrusions and mélange: these two processes—the accumulation of the spilitic-keratophyric association and the squeezing out of the ultrabasites—are independent of each other.

It seems to the present writer that geological reality is much better reflected in the views of Hans Stille, who first introduced the concept of eugeosynclines and initial magmatism and who considered the ophiolites proper to be an inseparable element of initial magmatism [24].

There are geosynclines with very different volumes of initial magmatism. As a rule, moreover, where the initial magmatism is small is volume (for example, in the Greater Caucasus during Alpine time), it is limited to the spilitic-keratophyric association without ultrabasic rocks, whereas the occurrence of the latter is always accompanied by abundant formation of rocks of the spilitic-keratophyric associations. One of the examples of such abundant magmatism accompanied by ultrabasites may be the Hercynian Urals. From this it naturally follows that the ultrabasites, in the first place, are an inseparable element of initial magmatism, and second, are an indicator of greater heating of the upper mantle. With less intensive heating, the magma-forming process is limited to the rocks of the spilitic-keratophyric association. This view will be additionally supported below. At this point, it must be said that we cannot dwell here on the mechanism of the ophiolites' ascent to the surface much about which is still unclear, and must confine ourselves to the supposition that this mechanism is in some way related to especially strong thermal activation of the mantle.

Eugeosynclines are characterized not only by initial magmatism, but also by great intensity of vertical block-wave crustal movements. This great intensity is expressed concretely in the large amplitudes, high velocities, and—most important—the great contrast of these movements. It is natural to suggest that the great intensity of the vertical crustal movements is due to great mobility of the asthenosphere material, which in turn is due to its considerable heating. It is quite likely that the block-wave oscillatory crustal movements are caused by diapirism of the asthenosphere; and this supposition naturally relates the intensity of the oscillatory movements directly to the temperature in the upper mantle. Consequently, not only the separation of mantle magmas, but also the high contrast of the vertical crustal movements, can be attributed to the strongly heated state of the upper mantle.

At this point, we find additional indirect evidence that the ascent of ultrabasic material corresponds to an especially high degree of heating of the upper mantle. The history of many geosynclines shows that the ultrabasic rocks are always confined to the zones characterized by the most contrasting vertical crustal movements. As a rule, the highest contrast in the development of such movements can be seen in the inner zones of geosynclines of the Alps and the Dinarides, in the Hercynian geosynclines of the Urals and the Appalachians, and in many other geosynclines. And it is to these very inner zones that the magmatic indications of a eugeosynclinal regime are likewise confined.

The correspondence between the maximum contrast of the vertical movements and the outcrops of ultrabasites can be seen not only in space, but also in time. The development of orthogeosynclinal regimes is usually preceded by a so-called pre-geosynclinal stage, which in the low contrast and differentiation of its vertical crustal movements, in the absence of magmatism, and in the character of its sedimentary associations resembles the platform regime. In the Alps, this stage of the Alpine cycle encompassed the Triassic and Liassic times, in the Hercynian Southern Tien Shan Range it covered the entire Early Paleozoic, and the pre-geosynclinal stage was likewise very prolonged in Southeast Asia and in the Verkhoyan-Kolyma region. This stage merged into the true geosynclinal stage only very gradually. The transition took the form of successive increases in differentiation and contrast of the vertical crustal movements and intensification of the part played by faults at depth, which transformed the wave-like oscillations into black movements. Against this background, at some stage the rocks formed in the initial magmatism appeared; these may also have included ultrabasites. This succession of events, it must be supposed, is determined by the gradual, constantly increasing heating of the upper mantle, beginning with the pre-geosynclinal stage. This once again supports the basic thesis of this paper, that each endogenic regime reflects a particular level of heating of the upper mantle.

In tracing the changing conditions in the transition from higher to lower levels of heating, it should be noted that the scale and contrast of the vertical crustal movements diminish, accompanied first by the elimination of signs of ultrabasite magmatism while spilitic-keratophyric magmatism is maintained, and then by reduction of the latter as well. Yet the vertical crustal movements, although in ever weakening form, are maintained and continue even in the miogeosynclinal, parageosynclinal and platform regimes. This form of manifestation of the upper mantle's activation turns out to be the most stable and persists even when the other forms have died out. The "cold" mantle accompanying platform regimes still retains sufficient mobility for the development of such structures as syneclises and anteclises.

THERMAL CONDITIONS IN THE CRUST AND ENDOGENIC PROCESSES

The "hot" state of the crust is manifested in the inversional stage of orthogeosynclinal regimes. It is in this stage that the processes of high-temperature metamorphism and anatectic granitization develop within the crust.

But there is reason to think that the heated state of the crust is not manifested only in metamorphism and granitization. It also affects the deformations of the crust. The inversional stage, in fact, is characterized, besides metamorphism, by the strongest plastic deformations of the crust: this is the time of maximum folding of the complete and deep types, as well as the formation of thrust sheets. This situation stands in sharp contrast to the regimes in which the crust is in a "cold" state: the deformations in a "cold" crust are predominantly of block character. Besides the platform or parageosynclinal regimes, a block character also characterizes the crustal deformations in orogenic and rift regimes, as well as during the pre-inversional stage of orthogeosynclinal regimes when the "hot" mantle is overlain by a "cold" crust. To be sure, the "cold" state of the crust in the pre-inversional stage of development of orthogeosynclines is underscored by the development of metamorphism of the "blue schist" facies, which indicates high pressure but low temperature.

The different character of the deformations of the crust in its hot and cold states can be ascribed to the differences in its mechanical properties that depend on the temperature. But the relation of the thermal state of the crust to its tectonic deformations can also be seen in more concrete form.

It has been pointed out repeatedly that an important part in the mechanism of folding is played by the phenomenon of "diapirism at depth" [4,18]. This is due to the occurrence, within the crust, of an inversion of densities through the effect of certain processes that are in turn produced by the action of high temperatures on rocks. The significance of diapirism at depth for the structures of old metamorphic rock bodies has been excellently demonstrated by V.V. Ez [25]. But this significance is no less in the case of the folded zones of Phanerozoic age. M. A. Goncharov [11], by experimental modeling, has shown that it is quite possible, in principle, for convective movements in a layered medium to give rise to deformations exactly like complete (similar) folding.

It has been shown that the diapirs at depth, which themselves have a complicated internal structure, much like the structure of salt domes, as they are injected into the overlying strata push them aside and at the same time buckle them into folds. An analogous action on the surrounding strata is exerted by the more monolithic crustal blocks elevated above the adjacent areas, if they are capable of gravitational spreading outward or laterally. These mechanisms of local causation of the horizontal compressive forces within the crust that are required for the formation of complete folding have also been successfully reproduced in models a number of times [12]. Such mechanisms are of fundamental significance for understanding complete folding, inasmuch as there is sufficient evidence against the concept of "external" pressure on the geosyncline, whether within the framework of the contraction hypothesis or that of plate tectonics [2,4,7,etc.].

But horizontal compression within the crust does not necessarily arise only where a certain mass of rocks is elevated above the others and thereby spreads out laterally through gravitation. The same gravitational lateral spreading can occur if the adjacent blocks are on the same horizontal level, but have different densities. Under these conditions as well, the denser material will flow toward the less dense, tending to press the latter upward. If a belt of the earth's crust made up of less dense material is situated between two blocks formed of denser rocks, when this belt and the two adjacent blocks are on the same horizontal level, the less dense belt will be pressed in the horizontal direction, deformed, and squeezed upward. The only condition necessary for this to occur is such plasticity of the participating crustal blocks as will enable this mechanism to be realized. Figure 1 shows the result of an experimental modeling of this mechanism in plastic stratified materials.

It is obvious that gravitational flow in the interaction of crustal blocks of different densities, be they on the same or on different levels, should develop especially readily where the rocks have the lowest resistance to deformation. Such lower deformation resistance may be due to relatively strong heating of the rocks, their abundant saturation with water, and their tectonic fracturing. All these three causes frequently act together: a tectonically ruptured zone becomes a path for the penetration of fluids carrying heat as they ascend from depth.

These conditions are the basis for the formation of the folding that has come to be called "near-fault folding." They are also responsible for the development of the so-called "zones of buckling." In both these cases, within a certain belt or zone in which the rocks are tectonically broken up by a dense network of ruptures and where the metamorphic phenomena and signs of hydrothermal processes testify to the penetration of hot solutions from greater depths, the beds turn out to be strongly buckled and folded, whereas in the neighboring area just outside this belt they lie relatively undisturbed. The cause of the

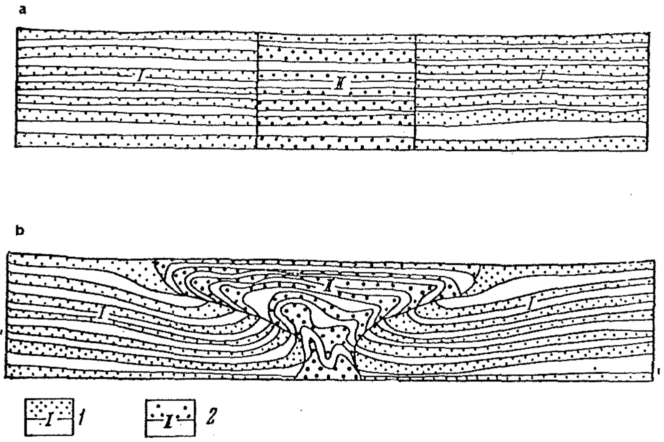

Fig. 1. Model reproducing local compression of middle, lighter block in lateral spreading of heavier blocks at ends, tending to restore gravitational equilibrium: a) initial form of sample; b) appearance four hours after beginning of experiment; 1) layered body consisting of mixture of 90% rosin (90 parts rosin, 10 parts oil) with clay (density 1.15 g/cm^3); 2) layered body of 80% rosin (density 1.0 g/cm^3).

deformation lies in the fact that the block of ruptured, loosened, and heated rocks has a smaller average density than the adjacent blocks of less fractured and colder rocks, and is thus crushed and squeezed between the latter.

The belts of near-fault folding and "zones of buckling" (which are, in essence, also "near-fault") are extensively developed under conditions in which a considerable part is played by faults at depth. For example, near-fault folds are developed in the zones of orogenic regimes along the boundaries between tectonic uplifts and depressions. Of special interest is the circumstance that the narrow belts of near-fault folding turn out to be the last manifestations of folding of the complete type where regional occurrences of such folding are absent. For instance, the great Taudeni syneclise, located on the Sahara plate in North Africa and filled with Riphean deposits, is fringed on three sides by narrow belts of near-fault complete folding of Baikalian age, whereas the whole interior of the syneclise has remained undeformed [19,20]. A belt of the same type of complete folding extends along the edge of the Jurassic Southern Fergana basin, along the Talass-Fergana fault bordering it; in the remainder of the basin, however, the deformations are expressed only as block folds. Many more such examples could be cited.

Yet the mechanism of compression of less dense parts of the earth's crust between areas of greater density is evidently not limited to cases of its local manifestation near faults within regions of generally undisturbed beds. It also acts in zones of regional development of complete folding, being linked in certain areas to other mechanisms of such folding that do not require density inhomogeneities. Evidence of this can be found, for example, in the structure of the southern slope of the Main Caucasus Range, in its southeastern part, where "splashes" of folds can be seen above the scarps complicating the slope (Fig. 2). Inasmuch as these scarps are associated with faults, such "splashes" are "near-fault" phenomena and are due to the action of the mechanism just considered above.

The phenomenon of "remobilization" of the basement is common in folded zones; this is due to the rocks' penetration and saturation by hot solutions and their consequent partial melting. Such remobilization has occurred widely, for example, in the Western Alps, where it has affected the pre-Alpine basement complex, whose plasticity as a result was increased so much that it participated intensively in the deformations of Alpine age, and particularly in the formation of thrust sheets of the Pennine type. Remobilization encompassed the zones that were intrageosynclines in the pre-inversional stage of the Alpine cycle. The character of the subsequent deformations indicates that such zones have been subjected to very strong horizontal compression, and their material has been squeezed out in the form of nappes. The rocks undoubtedly became less dense during their remobilization. Hence it is quite likely that in this case of very strong and regionally occurring folded

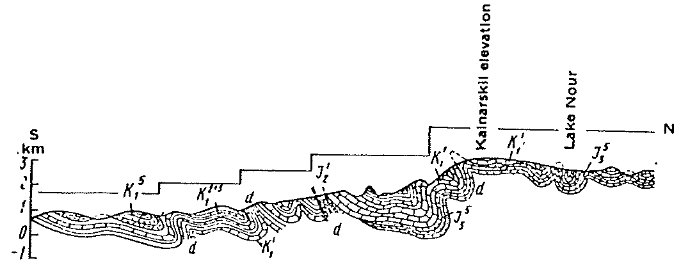

Fig. 2. Geologic profile of southern slope in southeastern part of Greater Caucasus (area of Mt. Nukha) (after A. V. Dolitskii). Dashed line above profile shows relative disposition of crustal blocks and scarps between them; *d* marks "splashes" of folds above structural scarps.

deformations, the mechanism of gravitational compression of the less dense ("de-densified") crustal blocks between denser parts of the crust has been of substantial significance. Moreover the role of the denser blocks conveying the pressure was played by the intrageoanticlinal massifs separating the intrageosynclines. These masses spread outward laterally and squeezed the less compact rocks located between them, beneath the intrageosynclines.

Thus complete folding can be regarded largely as the result of crustal deformations caused by density inhomogeneities. The latter arise mainly as a consequence of the uneven heating of the crust through the action of ascending streams of material from the earth's interior. The intensity of the heating and the width of the zone it encompasses govern the complexity of the folded deformations and their distribution. Hence, the regular link between folding and other characteristic features of the endogenic regimes, inasmuch as the latter on the whole depend on the thermal regime of the tectonosphere. Maximum heating of the crust accompanies the inversional stage of the eugeosynclinal regime. The latter is also characterized by the most intensive complete folding, accompanied by deep thrust sheets of the Pennine type. With less heating of the crust, as in the miogeosynclinal regime, the folded deformations are generally less intensive and are not accompanied by nappes of the Pennine type: the latter may be overthrust upon the miogeosynclinal zones, but their roots are located in adjacent eugeosynclinal zones. Thus, for example, the Pennine thrust sheets in the Western Alps have their roots in the Eugeosynclinal Pennine zone and have been overthrust upon the Helvetian miogeosynclinal zone. But the only thrusts of local, miogeosynclinal, origin are the nappes of the superficial Helvetian type. In parageosynclines, where the crust is considerably less heated even than in miogeosynclines, folding of the complete type either is lacking altogether or else is confined only to the narrow fault zones, where because of the increased crustal permeability the rocks are relatively more heated and thus less dense. In the same parageosynclines, and also on young and old platforms, the place of complete folding is taken by folding of the pressure and block types. The first of these is a superficial phenomenon caused by density inversion within the sedimentary deposits, its only connection with the processes at depth being that the most favorable zones for its development are located above structural scarps in the basement formed by vertical block movements of the latter, inasmuch as these zones are penetrated by faults, broken up by fractures, and thus decompacted.

The origin cause of block folding is unknown. Block folds may perhaps rise above areas of lowered density and increased volume of the material in the lower layers of the crust during such processes as, for example, the serpentinization of ultrabasic rocks or regressive metamorphism. In such processes an essential part must be played by water penetrating along faults from the surface or from depth. The degree of heating of the crust may also be of significance here. Block folds are therefore considerably developed in the relatively more mobile areas of platforms, where it can be inferred that the crust is more heated than in the stable regions of the same platforms.

RELATIONSHIPS OF ENDOGENIC PROCESSES IN SPACE AND TIME

The different endogenic processes existing at the same time as a rule form elongated zones at the surface of the continents. At any rate, zonality has been a characteristic feature of regimes since the beginning of the Proterozoic. Moreover, the different regimes are combined with each other both laterally (when the zones characterized by different regimes lie next and more or less parallel to each other) and proximally (when the regimes replace one another longitudinally along the strike of the zones).

One very commonly sees a lateral transition from a platform regime to a parageosynclinal, then to a miogeosynclinal, and finally to a eugeosynclinal regime. The zones of different regimes are disposed in this manner, for example, in the Western Alps, the Dinarides, the Appalachians, the Urals, and many other regions. Such a succession encompasses the platform and one branch of a complex geosyncline. Its opposite branch, adjoining another platform, may be disposed symmetrically, but is more often asymmetrical. In the Alps, for example, such a full succession of zones is characteristic of the outer branch, which faces west and north, whereas the opposite, inner branch, facing the Lombard lowland plain, can be considered almost entirely parageosynclinal in its development. Such a similarly sharply asymmetrical zonality can also be seen in the profile from the Dinarides to the Balkans and beyond to the Moesian platform still farther east.

Yet such a disposition of the zones of different regimes within a complex geosyncline, in which the more active regimes are closer to the axis of the latter and the less active are nearer to its periphery, is by no means always observed. In other geosynclines, the eu-, mio-, and parageosynclinal zones are irregularly mixed. Such a pattern is characteristic, for example, of Southwestern Asia, including the Taurus-Caucasus part of the geosynclinal belt.

Although in this region the areas of para- and miogeosynclinal regime are concentrated primarily along the northern edge of the geosyncline (as in the Greater Caucasus, the Elbrus, and the Kopet-dag ranges), they also in some separate areas occur farther south, and the eugeosynclinal regime appears along the numerous deep faults scattered through the whole geosyncline, and in some region in the extreme south approaches almost to the very edge of the platform (for example, in Eastern Turkey).

These two modes of distribution of zones with different regimes within a complex geosyncline are reflected in important features of its development. In the first mode, the geosyncline develops as one entire structural unit: in the inversional stage, one central uplift is formed within it and gradually involves the whole geosyncline as it expands. Such a pattern of development can be observed in the Alps and the Dinarides. In the second mode of distribution, the geosyncline breaks up into a number of zones that develop independently thereafter: each intrageosyncline has its own partial inversion. This situation can be seen, for example, in the Caucasus.

In cases when there is a median massif within the geosyncline, the eugeosynclinal development is usually concentrated at the edge of the massif, as happens in the Dinarides, where the eugeosyncline is pressed against the boundary with the Macedonian-Rhodope massif, or in Transcaucasia, where the eugeosyncline lies at the very edge of the Armenian massif.

On the basis of the above facts, it must be considered that the lateral combinations of regimes are determined by a corresponding zonal distribution of thermal inhomogeneities within the tectonosphere.

The combination (mutual transition) of regimes along the strike is no less widespread. The miogeosynclinal regime characteristic of the Alpine development of the main part of the Greater Caucasus is replaced at both ends along the strike by the typical parageosynclinal regime of the Caucasus meganticlinorium's southeastern and northwestern plunges. In these two directions the scale and contrast of the oscillatory movements diminishes, folding of the complete type gradually arises and disappears, giving way to pressure and then to block folding, and all signs of metamorphism of the rocks disappear. The structure of these parageosynclinal regions is determined mainly by structural steps, to the sutural faults between which the clusters of pressure folds are confined [9].

The passage, within a complex geosyncline, from one regime to another along the strike is a reflection of transverse structural zonality. Such transverse zones are common in geosynclines. Of special interest is the case in which the transverse zones intersect the entire geosyncline and continue on into the adjacent platforms.

An especially striking transverse structure is that of the Punjab-Pamir region, which intersects the Alpine mobile belt, extending from the old Indian platform in the south to the Hercynian Tien Shan Range. The geologic histroy of the entire belt between the Punjab region and the Pamir Range is quite different from that which developed east and west of it [10,14,15]. The Khazar region, which lies on this belt, was in the Early Mesozoic a transverse uplift that separated the basins situated on both sides of it—in the Himalayas to the east and in Afghanistan to the west. A similar picture can be seen farther north, in the area of the Pamir Mountains. As one approaches this from the west, from the

Turkmen-Khorasan Mountains and the Parapamiz region, the thickness of the Triassic and Jurassic rocks decreases [16]. The northern branch of the Alpine geosyncline wedges out, and the miogeosynclinal regime is replaced along the strike by a parageosynclinal regime. D. P. Rezvoi [17] has pointed out the special character of development of the still wider transverse belt extending from India northward the whole of East Asia, and called this belt "the great geologic divide of Eurasia." He also showed that as one approaches this "geologic divide," the orthogeosynclinal regime of Mesozoic age is replaced along the strike by a parageosynclinal, and in some zones even by a platform, regime.

A special type of proximal combination of regimes is represented by the so-called "reentrant angles of platforms"—a concept developed some time ago by N. S. Shatskii [21,22]. Within these "reentrant angles" there is a transition along the strike from an orthogeosynclinal through a parageosynclinal to a platform regime. Such a combination is that of the miogeosynclinal buried Donbass with the parageosynclinal exposed Donbass, and beyond that with the platform Dnepr-Donets syneclise. Even within the platform regime, along the same strike there is a transition from the more mobile Dnieper-Don syneclise to the more quiescent Pripyat syneclise. Another such "reentrant angle" mentioned by N. S. Shatskii is the combination of the Ouachita miogeosyncline with the Wichita parageosyncline in the southern part of the Middle West of North America. To these instances one may add still another, the transition from the orthogeosyncline of the Western Alps through the Vauconte parageosyncline to the young Epihercynian West European platform (Fig. 3). In all such cases, it can be readily seen that the transition from the more activated regimes to the more quiescent is marked by the loss, one after another, of the features characteristic of the former and retention of those typical of the latter, although even these too lose their intensity. It has already been said above that the most persistent process in this respect moreover turns out to be that of the block-wave oscillatory curstal movements.

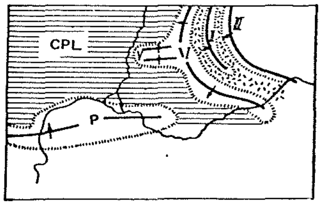

Fig. 3. "Reentrant angle of platform" formed by arc of Western Alps and Vauconte parageosyncline: P = Pyrenees, CPL = Central Plateau of France (Epihercynian platform); I) Subalpine zone, II) Helvetian zone, III) Pennine zone.

A general law that governs any or all endogenic regimes in their zonal distribution at the surface of the continents is their predominant alignment along certain selected strikes, which form a regular network. In another article [8], the present writer specially considers this matter and shows that the network made up of the strikes of "orthogonal" (meridional and latitudinal) and "diagonal" (northwest and northeast) orientations is persistently manifested in the disposition of the zones of all geosynclinal regimes or any age, beginning with the Archean.

In proceeding to discuss the relationships among endogenic regimes in time, it should be noted at the outset that the state of thermal excitation in the earth's crust always follows a stage characterized by thermal excitation in the upper mantle, with a "cold" crust. Moreover when the "hot" state arises in the crust, signs of cooling to the "cold" state begin to appear in the mantle. Such are the relationships between the inversional stage of orthogeosynclinal regimes and their preceding pre-inversional stages. Hence it follows that the heating up of the crust is the result of a heat wave traveling upward from the mantle. In view of what was said above concerning the different quantitative meanings of the terms "hot" and "cold" as applied to the earth's crust and mantle, it can be supposed that the change from a state of "hot" mantle and "cold" crust to the state of "cold" mantle and "hot" crust in no sense means that a thermal inversion occurs between the mantle and the crust: in the upper mantle the temperature drops to the level at which magmas cease to be melted out, but it still remains above the temperature that now arises within the crust. It simply means that the temperature gradient between the mantle and crust becomes less sharp than it was in the previous stage, and moreover that the temperature within the crust rises to the level sufficient for metamorphism to take place.

Although the "hot" state of the crust must necessarily be preceded and prepared for by a "hot" state in the mantle, the reverse is not obligatory: the situation of a "hot" mantle is by no means always followed by that of a "hot" crust. In the orogenic and rift regimes one finds all the indications of a "hot" mantle, but the crust does not become "hot". The deformations within the crust continue to be of block character, and no high-temperature metamorphism occurs within it.

The fact that in some cases the heat from the mantle enters the crust and heats up at part of it, whereas in others it has no such effect on the crust, may perhaps be attributed to the different character of crustal permeability in the two instances. In the case of a eugeosynclinal regime, the permeability of the crust has a dispersed character. Heat enters the crust with intrusions of mantle magmas and with mantle fluids penetrating the crust along a frequent network of lineaments in various directions, a considerable part being played by stratal intrusives with wide, heat-liberating horizontal surfaces. In the orogenic and rift regimes, by contrast, the crustal permeability is concentrated, owing to the relatively rare vertical faults along which the heat together with its magmatic and aqueous carriers penetrates readily right through the crust without really heating it (or heating it only in the immediate vicinity of faults), and is thence dissipated into surrounding space.

The action of a "hot" mantle on the crust is distinctively manifested in the history of median massifs. The latter are blocks consisting of a "cold" mantle and a "cold" crust. But they are located within geosynclines and in the pre-inversional stage are surrounded by "hot" mantle. Moreover, as was mentioned, the most activated areas of the mantle are in the immediate vicinity of the median massif. As a result, the median massifs are destroyed through the action of the "hot" mantle. Their edges are "broken off" and zones of subsidence appear in their place, often with an intensive development of ophiolitic complexes. Such collapse of the median massif's edges can be readily seen in the history of the Thracian mediam massif, located in the middle of the Dinaride-Balkan geosyncline. Collapse of the Thracian massif's western edge in the Late Jurassic led to the formation of the Vardar zone with its eugeosynclinal regime, and on the site of the same massif's eastern edge, the latter's collapse in the Late Cretaceous led to the development of the Sredna Gora basin. A similar history characterized the Armenian median massif, on the site of whose collapsed northern edge, likewise in the Late Cretaceous, the Sevan-Akera ophiolitic zone was formed.

The median massifs are not only "eaten away" at their edges, but are also broken up in their interior. Thus the initially single Thracian median massif became divided into the Pelagonian, the Serbo-Macedonian, and the Rhodope massifs, between which fault-zone basins with para-, mio-, and eugeosynclinal development arose. The break-up of the Armenian median massif resulted in the formation of the distinctive Trialety volcanogenic parageosyncline. This process of destruction of median massifs occurred widely during the Cretaceous period in Southwestern Asia. In the latter region, after the Baikalian geosynclinal cycle, a regime similar to that of platforms was established. But its further geologic history compels one to regard it rather as a regime of median massifs. In essence, what was formed here was an enormous median massif that abutted on the Arabian platform on the south, and extended from there northward all the way to the Greater Caucasus, to the northern part of Afghanistan and Iran, and to the Pamir Range. In the Late Cretaceous, variously oriented faults were formed within the body of this great massif, and around these faults arose narrow, isolated basins characterized by a eugeosynclinal development. It can be supposed that heating of the mantle beneath this vast massif led to its "dispersed" disintegration.

The history of the earth's crust on the continental can, in its largest features, be divided into three major stages: a permobile stage corresponding to the Archean; an unstable protogeosynclinal stage encompassing the Early and Middle Proterozoic on the northern continents and the whole of the Proterozoic on the southern continents; and a stable geosynclinal-platform stage that began on the northern continents with the Late Proterozoic and on the southern continents with the beginning of the Phanerozoic. In the first of these macrostages, activated endogenic regimes arose practically everywhere on the continents; during the second stage there were more and less active areas and zones, whose locations and disposition, however, were unstable; and the beginning of the third stage was marked by the formation of stable platforms, while within the geosynclinal belts opposed to them there was a process of successive reduction in the areas of formation of the activated orthogeosynclinal and orogenic regimes. Such an evolution, in the light of the previous remarks, indicates progressively increasing localization of the heating of both the mantle and crust. But it is essential to take note of two circumstances: first, that at any stage the orientation of the zones of activated regimes has been governed predominantly by the above-mentioned same regular network of orthogonal and diagonal directions, and second, that the reduction in area of the activated regimes did not lead to their breakdown into isolated, irregularly scattered separate spots. It led rather to the retention of increased endogenic activity all the way up to geologically recent time in two concentrated major zones—the Mediterranean-Himalayan belt and the Circumpacific ring, in whose disposition one cannot fail to discern some kind of geometric regularity, although its meaning is not clear.

Against the background of this change from one major stage to another in the endogenic development of the earth's crust, one can discern an endogenic cyclicity, which of course should be more properly termed quasicyclicity, since the durations of the separate "cycles" and many of their details differ. In spite of this, however, on the whole the phenomenon of cyclicity, as expressed in the multiple repitition of a certain basic succession of endogenic processes, cannot be doubted and is one of the most remarkable features of the history of the earth's crust.

Some previously cited publications of this writer [5,6,7] presented data showing that the endogenic cyclicity may be summarized as an alternation of epochs of thermal excitation and of recooling of the upper mantle. During its cooling, the endogenic regime at the surface may be described as one of either a "cold" crust (when the "cold" mantle is overlain by a likewise "cold" crust) or of a "hot" crust (when the "cold" mantle lies beneath a "hot" crust). It has been shown that the choice of these two possibilities depends on the character of the crust's permeability.

There are patterns of endogenic cyclicity—the Atlantic and the Pacific, each of them encompassing vast areas of the continents, where on the geologic scale of time one discerns a synchronous occurrence of the individual stages of cycles, determined by the activated or quiescent state of the mantle.

It follows, from the preceding discussion, that whereas the combination of different endogenic regimes in area is determined by the spatial inhomogeneities of the tectonosphere's thermal field, the change in regimes over the course of geologic time should be a consequence of time inhomogeneities of the same field, and the endogenic cyclicity must be produced by the changing character of the upper mantle's heating.

ON THE CAUSES OF THE SPACE AND TIME INHOMOGENEITIES OF THE TECTONOSPHERE'S THERMAL FIELD

Inasmuch as the whole endogenic development of the earth's crust is evidently determined by the tectonosphere's inhomogeneities in space and time, something must obviously be said about the possible causes of such inhomogeneities. These suggestions will, of course, be extremely hypothetical in character.

The heating of the upper mantle, which moreover is very different in different places and also changes with time, can occur only through convection—that is, by the ascent of heated material from greater depth. It has been suggested that the rise of such material into the upper mantle from the earth's deeper shells is a manifestation of the general process of differentiation of the earth's material, this differentiation being the very basis of the entire development of this planet. The source supplying such flows of material must evidently lie at the boundary between the lower mantle and the core [1]. Taking the temperature at which basalt is melted out from the peridotite in the upper mantle to be approximately 1400°C and assuming that at the boundary between the earth's upper mantle and its core to be close to 4000°C and that the adiabatic gradient in the mantle averages about 0.4°C/km [13], calculations show that the material ascending to the level of the asthenosphere will have a temperature of about 3000°C. If it is supposed that the upper mantle's temperature in its "cold" state is 1300°C, this means that (given the same thermal capacity of the cooling and heating material) the achievement of the temperature of 1400°C needed for the melting out of basalt requires the heating of a volume of the asthenosphere exceeding the volume of ascending material by at least ten times. According to A. B. Ronov's data [3], the volume of mantle magmas segregated during a cycle of a geosyncline's development requires that a volume of asthenosphere equal to a layer of 10-12 km within the geosyncline's area be drawn into the partial melting. Consequently, for melting to occur on this scale, during the geosynclinal cycle material must ascend to the upper mantle in such volume as to form a layer with an average thickness of 1 km in the geosyncline's area. These calculations are, of course, very rough and tentative, but they do show that such a mechanism of heating of the mantle is reasonable.

The alternation and variability of the epochs of heating up of the mantle and its cooling forces one to suppose that the ascent of heat-carrying material does not occur continuously and even less so at an even rate, but rather intensifies at some times and at others weakens, or occurs in separate portions. Moreover, the floating up of such portions takes place almost synchronously over large areas. There are apparently epochs in which this material accumulates at depth, being gathered into masses, and other epochs during which it bursts upward.

The existence of the above-mentioned regional laws characterizing the manifestations of endogenic regimes leads to the supposition that the floating up of portions of hot material from the deeper interior of the planet does not occur everywhere in equal measure, but only along a certain network of canals filled with material of lower viscosity (higher plasticity). This must be two to three orders of magnitude below the viscosity of the surrounding medium. This network has a regular orientation relative to the earth's axis of rotation, which determines the same orientation of the predominant strikes of the zones of activated regimes at the earth's surface. The need for the presence of canals of lower viscosity follows not only from the regular orientation of the zones of activated regimes, but also from other considerations. With a viscosity of the lower mantle of no less than 10^{23} poises and a density difference of 2 g/cm^3 between the surrounding medium and the lighter material segregated from the latter, even if it is collected into a sphere some 75 km in radius its ascent from the base of the lower to the top of the upper mantle would require about 200 million years, which is commensurate with the duration of an endogenic cycle. Moreover, the rate of ascent depends greatly on the volume of each portion, resulting in complete de-synchronization of the arrivals of hot portions of material in the upper mantle. Inasmuch as there must be at least some, however rough, synchronous correspondence of the epochs of heating of the upper mantle over wide areas, the medium through which the portions of hot material float upward must have considerably less viscosity.

The observed evolution of the distribution of activated endogenic regimes from one major stage of development of the earth's crust to another, and also within each such stage, presupposes a corresponding evolution of the network of deep canals of lower viscosity. Initially they must have been closely clustered and penetrated all the mantle regions beneath the continents, then their distribution must have shown an increasingly narrower localization that was at first unstable, and finally the active canals must have become concentrated within the Mediterranean-Himalayan and Circumpacific belts. It is beyond the scope of this article to discuss the development of the world's ocean regions, so that the evolution of the network of deep canals on the scale of the entire planet must be left unilluminated.

As for the origin of the network of deep canals into the earth's interior, this remains unknown. Likewise unknown are the reasons for the regular evolution of this network. Initially, the canals may have been formed under conditions of extension on a global scale, and there may have later been repeated circulation of heated material along them. With the course of time, one group of canals after another dies out, whereas others continue to be used. It is remarkable that the predominant strikes of the canals and the spatial direction of the evolution of their entire system are arranged along the present-day geographic coordinates—that is, they are ordered relative to the earth's present axis of rotation. Moreover the very same geometric ordering has been maintained over the whole course of geologic history. This phenomenon in and of itself, of course, is a categorical argument against any rotation of the continents such as is presupposed by the continental drift hypothesis. But the main thing is that here we face a highly interesting and complex geophysical problem, whose solution would shed light on the most fundamental hidden aspects of the development of this planet.

More detailed consideration of the distribution of zones with different regimes within complex geosynclines, in relation to the previous history of the same regions shows that the structural inhomogeneities left behind by earlier processes always have an effect on the subsequent distribution of the endogenic regimes. And if the new situation requires reorganization of the older structural plan, such reorganization does not occur immediately, but only after overcoming the resistance of past tendencies, so to speak. Concretely, one must speak of the "conservativeness" of vertical crustal movements. The earlier plan of these movements quite often for a long time still "shines through" the new plan superimposed on it. Examples of such conservativeness are: the "translucence" of the Paleozoic structures of the Ural-Oman transverse zone through the Alpide structures of the longitudinal Mediterranean-Himalayan zone in Iran, Afghanistan, and Pakistan; and the transverse Indo-Pamir bend, which is an "echo" of the Precambrian meridional tectonic strikes. To these examples can be added those described by N. S. Shatskii, specifically the wedging out of the foredeeps where they are superimposed on the platform anteclise adjoining the geosyncline, and the effect on the distribution of Jurassic thicknesses in the Greater Caucasus of the old basins and uplifts transverse to the strike of this mountain range; these basins and uplifts were still reflected in the structure of the adjacent part of the platform [23].

Vertical crustal movements are evidently accompanied by such structural or material changes in the crust as are only gradually "resorbed" when the plan of distribution and orientation of these movements changes. This problem has many different aspects, which cannot be discussed here.

In summing up, it can be concluded that all the various endogenic regimes at the surface of the continents and their entire variability in space and time must be explained mainly by the space and time inhomogeneities of the tectonosphere's thermal field that in turn arise as a result of uneven (again in space and time) differentiation of the earth's material. Moreover, there are enough data to permit one ot state that the variations in the course of the differentiation and inhomogeneity of the thermal field during its distribution and development are governed by finite laws, particularly those spatially related to the earth's axis of rotation. One can also discern the effect of the structural inhomogeneities that arose within the tectonosphere during the preceding history of the endogenic processes on the subsequent development.

What this amounts to is the action of a smoothed out global mechanism that even now can in some measure also be considered in the form of a quantitative geophysical model. To this end there are available some data, if only approximate, on the main properties of the tectonosphere's substance, on the temperature in the crust and upper mantle, on the distribution of the heat flows in different regions of the continents, and on the rates, amplitudes, and contrast of the vertical crustal movements under different endogenic regimes.

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