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Title: NEW TRENDS IN THE DEVELOPMENT OF STRUCTURAL GEOLOGY by

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NEW TRENDS IN THE DEVELOPMENT OF STRUCTURAL GEOLOGY

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1. The Theory of Rock Deformation

The Becker Hypothesis. Up to this time, deformation of rocks has been investigated primarily by use of the Becker hypothesis (1893). The basic principle of the latter is that in homogeneous deformation of an isotropic body, the sphere described in this body will change in the general case into an ellipsoid. Becker restricted his study by two conditions: 1) that the deformation be biaxial or planar, i.e., the mid-axis (B) of the ellipsoid does not change, remaining constantly equal to the sphere's radius; and 2) the volume of the body remains constant. Two methods of applying the deforming forces, pure shear and shear, are considered.

The important conclusions which result from Becker's analysis are:

1. Deformation is accomplished by slippage along two conjugate systems of circular cross-section of the ellipsoid and, thus, the surfaces of slippage make some oblique angle with the directions of the major and minor axes of the ellipsoid.

2. There are no normal stresses on the surfaces of slippage, and thus the volume neither increases nor decreases in deformation.

3. Displacement along surfaces of slippage occurs so that matter moves inwards on the sides of circular cross-section which face the minor axis (the compression quadrant) and outwards, relative to the central part of the ellipsoid, on the sides facing the major axis (tension quadrant).

4. Under the action of a couple (shear), slippage develops primarily along one system of circular cross-section. One-system shear structures form.

Criticism of the Becker Hypothesis. When we inspect the actual conditions under which rocks are deformed, we see that the deformation is infrequently homogeneous, the rocks themselves are not ordinarily isotropic, plane deformations are rare, and constant volume under deformation is more often the exception than the rule. Finally, pure shear stress is extraordinary and never occurs in nature. (As is known, in pure shear, the body is subject to a compressive force in one direction and a tensile force equal in magnitude in another direction). Actually, many deformations occur where there is only one possible direction of movement, namely, upwards towards the surface. In this case, normal stress components arise on the surfaces of slippage and the volume of the rocks changes.

Therefore accurate calculations, especially in connection with the very important problem of how coal forms conjugate systems of shear fissures in the direction of greatest shrinkage, cannot be based upon the Becker hypothesis. It is characteristic that even Becher (1920) tried to solve the problem of the angle between conjugate shear surfaces by using Moore's circular diagrams instead of Becker's hypothesis.

2. Considerations on the Development of a Theory of Rock Deformation

The idea of a deformation ellipsoid is useful in the development of a theory of rock deformation, but it should not be used as it was by Becker.

The above considerations show that the pure mathematical analysis used in Becker's hypothesis is not legitimate, inasmuch as the conditions governing rock deformation in nature do not correspond even approximately to the conditions adopted in the hypothesis.

The idea of a deformation ellipsoid as a figure characterizing deformation must be changed in the light of recent data. Study of rock deformation in folded regions has indicated that the characteristic deformations are triaxial, in which shrinkage occurs along the B-axis as well as the C-axis. Shrinkage occurs not only in a direction perpendicular to the long axes of the folds, but also in the direction of strike of the folding.

Fissures in folded regions indicate this type of deformation. The fissures and shear surfaces usually develop not only in the zone of the B-axis, but also in the zone of the C-axis, forming systems of conjugate fissures or surfaces of slippage because of shrinkage along the B- and C-axes.

In many cases, the surface of the ellipsoid in no wise reflects the type of deformation which has occurred, and therefore the idea of a deformation ellipsoid does not have anything approaching universal application in the analysis of rock deformation. Thus, we frequently must limit ourselves to the three main axes of deformation (A, B, and C), without clarifying the deformation magnitudes in other directions.

Criticism of Becker's hypothesis forces one to conclude that a single theory of deformation is inadequate and that, as a whole, the theory must be developed by one's admitting the existence of at least two quite different types of deformation; namely, 1) elastic deformation changing into brittle deformation and leading to slippage and faulting without substantial plastic flow, and 2) elastic deformation, changing into plastic. The idea of deformation by means of shearing along systems of planes which form an oblique angle with the axes of the deformation ellipsoid is applicable basically only to the first type of deformation.

If the rocks are deformed plastically, slippage takes place along planes parallel (or nearly parallel) to the direction of maximum elongation. Thus, one-system slippage is not always the result of shear (i.e., the action of a couple), as was assumed by Becker and Schmidt (1932), but can also be the result of plastic deformation. In the last case, the ellipsoid does not even show the final form of the deformed body roughly, because the original sphere is transformed in the deformation process into a body of complex form, elongated in the direction of flow. And even though any plastic deformation unavoidably includes elements of elastic deformation because it does not change into brittle deformation, very rarely do we find in rock even relic traces of slippage along two systems of shear surfaces at an oblique angle to the direction of maximum shrinkage.

Thus follows the important conclusion: surfaces of slippage make an oblique angle to the direction of maximum shrinkage of the deformed body only when brittle deformation predominates, while for the case of predominant plastic deformations, they are perpendicular to the direction of maximum shrinkage. Therefore, the discussions, started by Becker and Van Hayes in 1893 on the orientation of cleavage surfaces and which have continued up to this day, are actually pointless, because both Becker and Van Hayes were right within limited regions. Disregarding details, we can consider that under brittle deformation some varieties of fracture cleavage develop along surfaces of slippage which make an oblique angle with the main deformation axes (this is cleavage caused primarily by inter-stratum slippage in folds). Flow cleavage and the remaining part of fracture cleavage which is closely connected with flow cleavage develop because of slippage in the AB-plane of the main deformation axes in plastic flow.

There is one more important circumstance governing the development of a contemporary theory of rock deformation. We have seen that the type of deformation changes radically depending upon whether brittle deformation or plastic deformation predominates. Homogeneity or heterogeneity of the deformed substance also affects the type of deformation markedly.

But, just as there are no rocks always with the properties of elastic, brittle, or plastic materials, so there are practically no rocks which always deform either homogeneously or heterogeneously. We can only talk of the conditions under which any rock is capable of deforming eleastically or plastically or as a brittle material. In the same way, any complex, even of very heterogeneous rocks, will deform as a homegeneous body under certain conditions;conversely, under other conditions, negligible heterogeneity will be observed in the deformation of highly homogeneous rocks. Therefore, the analysis of states, and not of the properties of deformed rocks, is of predominant importance in structural geology. The properties themselves to a certain measure are the result of states and are not invariant.

Elastic, plastic, brittle, homogeneous and inhomogeneous deformations are found in all parts of the earth's crust, both in the horizontal and vertical directions. However, despite the universality of deformations of all types, it is sometimes possible to isolate zones where some deformations predominate over others, and then it is expedient to speak of zonal distribution of types of rock deformation.

Spatial zones cannot always be isolated because the physico-mechanical properties and bedding depth of rocks are not the only factors. Another no less important factor is the speed of deformation, which may change sharply in the different periods of structure formation in a certain section.

In connection with the latter, we constantly find effects where deformations of one type are superposed upon deformations of another type, i.e., brittle on plastic or plastic on brittle, and the zonal scheme may become cloudy or may even take on a completely different form from that which would be expected if only the depth factor were taken into consideration.

3. Plastic Deformations of Consolidated and Crystallic Rocks

That plastic deformation is widespread among low-consolidated rocks which have not undergone diagenesis is acknowledged by most geologists, and their appearance is usually considered a sign of folding. There is a more or less widespread opinion that strata which are once crumpled into folds react to new mountain-building movements only by the formation of fractures. The possibility of plastic deformation of massive crystallic rocks is completely disregarded by many.

Actually, in number of regions, there is almost no plastic deformation among consolidated and crystallic rock and, of course, the idea that plastic deformation develops only with great difficulty among such rocks is in general justifiable. Nonetheless, in other regions there are exceptionally strong manifestations of plastic deformation among consolidated and crystallic rocks, and therefore we must again emphasize that no rocks have permanent physico-mechanical properties; the type of deformation is determined substantially by their state and the way in which the forces are applied.

For example, in the eastern part of the Central Caucasus, orogenic movements in the Miocene and Pliocene were accompanied by the active participation of ancient Paleozoic granites in the folding of Mesocenozoic rocks. This applies not only to structures of the first order, i.e., foundation folds having large radii (as Argan understood them), because we often observed folds of the second and even of the third order where folding began in ancient granites. We know of strongly compressed folds measured in the hundreds of meters where the dip angle of the limbs is 50-70°; sometimes those folds are even overturned. Among the larger plicated structures, we find fan-shaped folds with sedimentary rocks dipping beneath the granite in which folding originated.

The ancient granite surface in the Central Caucasus was initially a peneplain. Basal Jurassic strata of comparatively slight depth were found everywhere on it. We can judge the stratigraphic nature of the contacts between the granites and Jurassic strata which were deformed during folding by the permanent presence of these basal strata. Only in the last phases of warping into folds and considerably later did faults form, some of these faults being almost combined with the folding, and some clearly intersecting it.

Structural and petrographic study of granites reveals that granites which participated in folding were subjected to plastic deformation or crushing resulting in cataclastic or mylonitic structure. Plastic deformation, apparently, predominated, as reflected by jointing of the cleavage type parallel to the axial planes of the folds and by the greater degree of orientation of quartz grains in granites, which usually reaches 5%. Cataclastic or mylonitic crushing took place mainly in the extremely narrow (a few meters) zone of contact of the granites with the sedimentary rocks.

The plastic deformations in granites must have occurred at comparatively great depths (several kilometers) and were apparently affected by the high temperature caused by the introduction of neo-intrusive masses. In the western parts of the Northern Caucasus (the Kuban River basin, etc), where the depth of the crystallic foundation could hardly have been substantial in upper Tertiary time and there were very few neo-intrusions, granites did not participate in folding, and we find mainly fault-block tectonic forms and foundation folds of great radius.

In order to understand the genesis of plastic deformation of granites in folding, it is important to note that folds originating in granites are quite common in the general system of folding of Mesocenozoic rocks. There are no indications that the system of folding of sedimentary strata has been disturbed in places where the granite rocks are comparatively near the surface. In addition, folds originating in granite have all the characteristic morphological features of folds of sedimentary rock which are comparable to the former in magnitude (order). When folds of sedimentary rocks are asymmetric and have a regular overturning direction in certain zones, folds originating in granites overturn in the same direction. The echelon arrangement of Mesocenozoic folds is also characteristic of structures where folding originated in granites. Again, concentration of anticlines (and in other cases synclines) on lines tranverse to the general strike of the range is common for folds of the Caucasus where echelon structure predominates. This led to common undulation of structures along the strike of the fold with local crests and troughs of the whole tectonic structure. Finally, the brachyform nature of Mesocenozoic folds is repeated by folds originating in granites.

From this standpoint, the more or less strongly compressed troughs transverse to the main strike and emphasizing brachyform structure are of special practical interest. Transverse troughs are found not only in sedimentary Mesocenozoic rocks, but also in granites from which folded structures originated. Our observations have revealed that transverse troughs, which are usually later complicated by disjunctive dislocations, are ore-bearing in a number of cases. This broadens our potentialities for searching for new hidden ore deposits of the Caucasus.

Another important practical consequence of determining plastic deformation in consolidated and crystallic rocks is the possibility that disjunctive fault tectonics can be correctly analyzed. The amplitude of displacement along faults is often greatly overestimated when the amount of plastic deformation preceding the faulting is not taken into consideration. In addition, these principles will help to explain the extremely rapid decrease of displacement amplitudes which is often observed along the strike of faults.

4. Unconformable Folding

When the collapsing rocks in the formation of folded structures are strata with different physico-mechanical properties, the folds in each stratum have different forms. The practical importance of correct interpretation of disharomonious phenomena (which we propose to call unconformable folding) is very great.

In the first place, disagreement between folds of two strata is often mistakenly taken as a sign that there were two folding epochs with unconformities between the strata. For example, unconformity in bedding details of Liassic and Middle Jurassic clay shales and limestones (close to the surface) in the Northern Caucasus was explained without sufficient basis by the existence of considerable pre-Callovian folding, even though pre-Callovian movements were comparatively slight in this region, being expressed mainly by fault block displacements.

In the second place, unconformable folding is in many cases accompanied by the development of original interformation disruptions and brecciation zones which may be ore-controlling structures.

The intensity of disharmony in folding varies within wide limits, i.e., from scarcely noticeable displacements up to complete collapse of entire formations from the lower base or from the covering rock or directly from both interformation surfaces accompanied by formation of completely independent folded forms. An example of such a high degree of unconformity is the warping of a stratum of Famennian limestones interbedded with marls in the Kara-Tau mountains in northwest T'ien-Shan. This stratum, about 900 meters deep, lies between underlying Devonian sandstones and quartzites and a covering stratum of crudely-stratified Carboniferous limestones. In this structure, the collapse took place both from the base and from the covering stratum.

In the Transcaucasus, the Allaverdsko-Shamlugskiy region is very interesting from the standpoint of interformation collapses. The degree of disharmony here is not very great, but small independent movements during folding of comparatively rigid strata of Jurassic effusives, on one hand, and Jurassic sedimentary rocks, on the other, led in some case to the development of interformation zones of tectonic breccia and in other cases to interformation overthrusts of small amplitude. Both are ore-controlling formations. In the Allaverdskiy deposit, a folded interformation overthrust, which follows closely the stratigraphic contact surface between tuffaceous breccia and covering sandstone but at the same time forms a slight scale in the tuffaceous breccia, separates the rich part of the ore-bearing zone from the non-ore part, thus controlling localization of ore columns. In the Shamlugskiy and Akhtal'skiy deposits, the ore bodies are found directly at the surfaces and breccia of the interformation disruptions between different levels of the Jurassic sedimentary-effusive stratum. Moreover, it turns out that the Shamlugskiy and Akhtal'skiy deposits are situated in different stratigraphic stages of the folded structure, which opens up new potentialities for searches for "blind" ore deposits in the vertical as well as the horizontal direction.

5. Prototectonics of Intrusive Massifs

Because numerous ore deposits, especially deposits of rare metals, are found in fissure systems in intrusive massifs, and since the intrusive massifs themselves are localized in the upper regions of the earth's crust in connection with definite tectonic processes, the structure of intrusives is of great theoretical and practical interest. The works of Soviet geologists A. A. Polkanov (1935 and 1945) and N. A. Yeliseyev (1935) on the structure of intrusives are well-known. In this paper, we can discuss only three problems in this important subject.

Prototectonic structures are structures which form during and immediately after solidification of the intrusions. They thus reflect the system of tectonic stresses prevailing in the last stages of solidification of the intrusive massif. In connection with the latter, the systems of prototectonic fissures forming in the intrusive body can be correlated with lines-parallel or system-parallel textures (with the rock orientation), indicating the direction of magma flow immediately before solidification. Longitudinal fissures S follow the orientation and, being perpendicular to the pressure, remain closed. Transverse fissures Q are perpendicular to the line-parallel textures, strike out parallel to the direction of pressure, cannot be closed by the latter, and therefore are partly filled with veins and dikes of aschistose and diaschistose rocks.

These quite clear principles are constantly overlooked; not only prototectonic fissures, but also all other fissures of different age and derivation which are filled by veins and dikes, are called Q fissures. In these cases, the geologists forget that in most intrusive bodies, there are usually veins and dikes which form later in connection with newer magmatic cycles, along with veins and dikes of the intrusion which are genetically directly connected with the magma. Fissures containing young veins are not always

Q fissures. We must be still more careful in classifying S fissures because of the well-known ability of any rock, including granitoid rocks, to "close up" joints. If a granite massif was in a zone of submersion after its formation (at depths of over 4-6 kilometers) and was covered by thick sedimentary rock strata, the initial jointing may be destroyed partly or completely, as has been established in the case of the ancient granites of North Osetia in the Caucasus. When these granites shift into upper zones because of tectonic movements, new systems of fissures form in them which do not necessarily follow the systems of prototectonic origin.

The Genesis of S-Fissures. These fissures in their morphological features are somewhat similar to cleavage fissures, but they are perpendicular to the direction of maximum shrinkage, which contradicts generally-accepted ideas on the orientation of cleavage fissures. The latter, as is known, are situated at an angle slightly greater or less than 45° with respect to the C-axis of the deformation ellipsoid and, in any case, the angle is different from 90°. Like fracture fissures, S fissures cannot be classified by theoretical stress analysis assuming homogeneous deformation and are apparently caused by endogenous-inhomogeneous deformation. When heterogeneous matter undergoes compression in the direction of the C-axis of the deformation ellipsoid, it is elongated differentially in the perpendicular direction because of differences in the mechanical properties of the material in the different parts of the deformed body. As a result of this differential elongation, shearing stresses arise in the planes perpendicular to the direction of pressure. If the elastic limit is exceeded, fissures are formed perpendicular to the pressure.

Fissure Structures in Anorogenic and Orogenic Intrusions. Typical systems of prototectonic Q, S, and L fissures, according to studies by G. L. Pospelov, B. P. Belikov, and others, are observed only in those intrusive granitoid massifs which did not undergo substantial tectonic stresses after being introduced into the upper regions of the earth's crust. A much more complex picture is observed in granites of orogenic regions, i.e., the Caucasus, Altay, T'ien-Shan, etc. In these there are numerous fissure systems which are very haphazardly connected with the structures having prototectonic orientation of rock-forming minerals. The classification of prototectonic structures can seldom be applied satisfactorily to these massifs for two reasons: either (a) the fissuring which developed in orogenic regions still in the prototectonic phase is considerably more complex than fissuring of anorogenic intrusions because of the greater intensity of tectonic movements or (b) the more recent superposed fissuring obscures the prototectonic fissures structures and does not permit them to be restored in their original form.

For granites of orogenic regions, we emphasize especially that it is impossible to use the classification of fissures unless their prototectonic character and regular correlation with the orientation of minerals which formed in the last phases of flow of the solidifying intrusion is proved first.

6. Two Basic Trends in the Development of Structural Geology

Structural geology has long since passed the stage of description and classification of phenomena, unavoidable when any branch of science starts to develop, and now attempts to solve its problems by understanding the genesis of geological structures. Structural geologists have their own methods (kinematic analysis using the three main deformation axes as coordinates and the method of petrotectonic analysis) at their disposal. Their importance should not be overestimated, however, as they aresstill in the class of auxiliary methods.

The above review of some new trends in the development of problems in structural geology, despite its brevity, shows clearly two basic trends in its development: 1) an attempt to use the experimental and theoretical data of the engineering sciences (even to developing this data independently) in the field of deformation of matter and 2) broad synthesis of local observations in structural geology and the results of regional geological studies. Both of these trends represent nothing especially new. Looking back, we see that the classics of geology usually were written by these two methods, i.e., by combining broad geological studies with experiments on deformation of rocks under laboratory conditions. Conversely, we have as an example the failure of some Western European schools which have developed tectonic hypotheses from data of Alpian geology without considering the deformation mechanism and the engineering approach in the solution of basic problems. The result was numerous contradictory speculative hypotheses, often unsatisfactory from the standpoint of the simplest laws of physics and mechanics. That is why harmonious combination of experiment and geological observations is compulsory for Soviet researchers working on structural geology.

7. New Trends in the Use of Structural Geology for Deposit Exploration

The important role of structural geology in searches for mineral deposits is well-known, and we will not consider this problem as a whole here. There is, however, one practical problem upon which little has been done, although its future importance can hardly be overestimated. This is the problem of searches for "blind" deposits, i.e., those hidden from direct observation. Many large capitalistic countries, having exhausted their mineral resources to a considerable degree, are now using drill prospecting beneath structures for searches for new hidden deposits. For example, in one gold-bearing region of Canada, more than 15 kilometers of exploration wells have been drilled in the past few years in order to check for possible ore in the geological structures (according to S. S. Smirnov).

With the vast natural riches of the Soviet Union, we do not have to think about exhausting our resources, but under the conditions of the planned economy, it is expecially important that we obtain a scientific method of searching for new deposits. This scientific method will permit us to regulate the growth of the raw-material base for the mining industry in regions where this might be necessary and which are the most promising according to geological data.

Searches for hidden deposits involve large capital investments and high risk, and therefore they can be organized only on the basis of the proper geological studies and primarily, studies of structural geology.

The main characteristic of the use of structural geology for searches for hidden deposits is the combination of a thorough study of known deposits with a study of the geology of a large region. The actual problem in most cases will be to determine the position of known local ore-bearing structures among geological structures of regional scale and, from this, to establish the places in which the same ore-bearing structures might be found, i.e., structures in which ore bodies and deposits which do not come out to the surface might be concentrated.

Suitable attention must be given to the study of the characteristics and genesis of the geological structure of large regions in order for the regional geological surveys to answer the requirements imposed upon them. Study of the stratigraphy and distribution of facies of sedimentary rocks and the composition and form of bedding of magmatic rocks must not be a goal in itself, but rather a means to understand the geological structure.

Therefore, at some stage, the study of geological structure will begin to determine the trend of further stratigraphic, petrographic, and other studies, dictating selection of subjects whose development is necessary for understanding the structure and consequently for aiding solution of practical problems in searches for hidden mineral deposits.

We note also that the geological studies should be supplemented by a thorough study of characteristic changes of the country rock in known ore deposits in the exploration region, because the most important confirmation a hidden ore formation is that there be similar changes of the country rock.

Soviet geological science has the task of providing a raw material base for the needs of the economy. Successful solution by structural geology of the problem of searches for hidden deposits will facilitate accomplishment of this task.

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