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A Study of the Kinematics of Linear Folding (on the Example of the Southeastern Caucasus)

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The method proposed enables the kinematics of linear folding in the cover of sedimentary rocks in geosynclines to be divided into two components: external compression and reduction of the width of the zone, and advection caused by density inversion. The method uses structural criteria: the dip of the axial plane of the folds, the dip of the fold system level, and the amount of horizontal reduction of the folds, all of which can be found both in natural structures and in experimental models. Testing of the method on experimental models of external shortening and advection has shown the reliability with which these two components can be distinguished. A study of linear folding in the southeastern Caucasus based on the example of nine geologic profiles demonstrates the significant magnitudes of both advection and external shortening. Structural profiles, measurements of structural features, formulas and the results of calculations, and a nomogram for determining the magnitude of advection are presented. The independent and self-contained character of both components of the mechanism of linear folding are shown.

STATEMENT OF PROBLEM

Folds and folding have attracted the attention of geologists for about two centuries, but up until now no single view of the origin of these structures has been universally accepted. At present the most firmly rooted may be considered to be the historically developed concept that folds are formed as a result of the horizontal compression of the more plastic portions of the Earth's crust (geosynclines) that are squeezed between more rigid blocks (platform or median massifs). One basis for this view is the simple and, at first glance, logical consideration: any fold taken in isolation that is seen in the field was clearly formed as a result of horizontal compression, in general, and since in a folded region such folds continuously replace each other across strike, the entire folded region must also have been formed as a result of horizontal compression. It is well known, however, that a number of essential distinctive features of the structure and history of geosynclines cannot be explained within the scope of these views.

Many distinctive features of folded complexes can be interpreted as the result of the action of volumetric forces of gravity. The latter cause not only sliding and accumulation of bedded rocks down the slopes of tectonic uplifts (for example, in the form of rock sheets of gravitational character), but also the flotation of lighter rocks within heavier ones to form structures of diapir character under conditions of density inversion, when the heavier rocks overlie the lighter. Such diapirism at depth has recently drawn the attention of a number of researchers [1, 3, 10]. This process appears to be a kind of unidirectional convection: The lighter material rises and remains above, whereas the heavier material sinks and remains below, so that the complete, to say nothing of repeated, circulation typical of ordinary convection does not occur. Such diminished or abbreviated convection has come to be called advection. Both the beds in the cores of the diapirs that rose and those in the surrounding rocks pushed aside by the diapir are buckled into folds. It has been suggested that advection plays an important, and perhaps the leading, role in the mechanism of development of folded zones.

The causes of density inversion are various. They are probably associated predominantly with uneven heating of a series of sedimentary rocks, and the resulting generation within them of a geothermal gradient such that the deeper-lying beds turn out to be considerably more strongly heated that the overlying rocks. The expansion of their pore waters, the supply of volatiles, and the additional segregation of constitutional water into the pores from the alteration of minerals lower the overall density of the rocks in these beds to a degree sufficient to start advection. These questions are most thoroughly considered in the publications of M. A. Goncharov [3], who also developed a very simple mathematical model of advection (Fig. 1) that reveals the character of the deformation processes arising within it.

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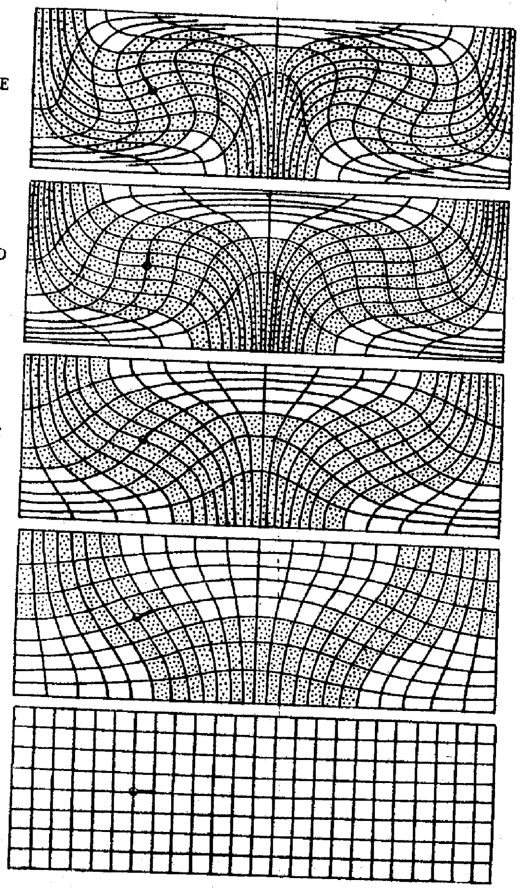

Fig. 1. A very simple mathematical model of advection (A-E) (after M. A. Goncharov [3], with some alterations); dots show areas in which folds are formed.

Consideration of this scheme shows that in advection the beds can be subjected to longitudinal compression and are consequently buckled into folds without any reduction of the total width of the whole advected series: that is, without the action of any external compressive forces. The longitudinal compression occurring at one level is compensated within the same series by longitudinal extension at other levels (Fig. 1). In nature these areas of extension may be eroded away or not exposed, so that they are overlooked. Thus, the advection process is capable of leading to the development of linear folding without external shortening of the folded zone.

This very simple mathematical model of advection is capable of quantitatively predicting the possible degree of compression of the folds and the spatial positions of their axial planes and fold system levels. The present author has made such calculations for a number of natural folded complexes in the southeastern Caucasus and the Tien Shan Range. These showed that the compression of individual folds in nature has systematically exceeded the values characteristic of advection in its pure form. Meanwhile, the antivergent style of the structures studied and the combination of slightly compressed large synclines on the margins of structures with intensely deformed folds in the central large anticlines were evidence that advection took part in their development. Especially convincing was the presence of second generation folds on the flank of the Turkestan anticlinorium in one of the Tien Shan profiles [6], which is fully consistent with the scheme of advection in long-past stages of development and can in no way be explained by external shortening. These excess values of the compression of individual folds in comparison to what they ought to have been in pure advection suggested the possible combination in nature of what investigators commonly believe are the two mutually exclusive processes—advection and external compression.

The development of this idea led to the creation of a method of kinematic analysis of linear folding, in which both advection and external shortening of the folded zone are present equally. In other words, the new concept is that folding occurs as the simultaneous result of a redistribution of volumes of material without change in area of the folded zone and of a transverse shortening of this area. The main task in this approach is to find some way of separating the "internal" advective component of folding from the portion of folding that is due to external shortening. It is clear that such a method must be quantitative and not qualitative. If folding in nature is of purely advective origin, the result will be "zero" transverse shortening and some "quantity" of advection. On the contrary, if the folding arose as a result of transverse shortening alone, this situation will be manifested as "zero" advection and some "amount" of external shortening. In other cases, one must suppose the combined action of some "quantity" of both.

As criteria for such a distinction between the mechanisms of folding, the following were chosen: the correspondence between the amount of external shortening of the individual folds along the profile (passing through any object of linear folding, whether natural or experimental) to the amount of external shortening of the whole profile. In pure external shortening (of which the simplest case is the convergence of vertical walls or props), these two magnitudes will coincide. In pure advection, although external shortening does not occur, folds arise and the amount of external shortening is the greater the farther the advection process has gone. In the case of a combination of these processes, the average amount of transverse shortening of the individual folds along the profile turns out to be greater than the amount of external shortening of the profile.

ANALYSIS OF M. A. GONCHAROV'S MATHEMATICAL MODEL OF ADVECTION

The proposed kinematic model of linear folding is based on the very simple mathematical model of M. A. Goncharov, which merits detailed discussion. This model of advection is based on the following assumptions.

1. The advective layer is horizontal. 2. The advective layer is homogeneous. 3. The properties of this layer are equivalent to those of a viscous Newtonian liquid. 4. The layer is heat-conductive. 5. The layer has boundaries that are free, flat, and of equal density. 6. The conditions of advection correspond to a small excess of the first critical Rayleigh's number, causing the rise of a convective "arch" (and not isometric hexagonal cells).

The introduction of these presuppositions has made it possible to write very simple equations of hydrodynamics, whose solution in the Bussines approximation in the linear formulation yields the velocity field of the movements of the particles in the convective arch [3]:

$$V_x = -A\left(\frac{\pi}{h}\right)\sin\left(\frac{\pi z}{h}\right)\cos\left(\frac{2\pi x}{\lambda}\right),$$

$$V_z = A\left(\frac{2\pi}{\lambda}\right)\cos\left(\frac{\pi z}{h}\right)\sin\left(\frac{2\pi x}{\lambda}\right),$$

where V_x and V_z are, respectively, the components of the vector of the velocity along the horizontal axis x and the vertical axis z (along the convective arch the rate of movement of the particles V_y is zero), h is the height of the convective layer, λ is the wavelength of the characteristic disturbance, and A is a certain constant. The ratio of the vertical to the horizontal sides of the cell was taken to be 1:1.5.

To study the deformations this formed, M. A. Goncharov uses a square grid (Fig. 1, A). The movements of the nodes of this grid were calculated by the above formulas for certain particular time segments. The new positions of the nodes were joined by lines, and the picture thus formed clearly demonstrated the deformations within the advective cells in these stages (Fig. 1, B-E).

It is assumed that all the areas of initially square shape (Fig. 1, A) are filled with horizontal beds. Then the elongation of the initially vertical sides of these areas in the subsequent stages means that the beds have undergone longitudinal compression, and this in turn means that folds have been formed in them (as shown by the dotted areas in Fig. 1). Shortening of the vertical sides indicates extension of the beds and the absence of folds (areas not dotted). It can be readily seen from Fig. 1 that the number of areas occupied by folds gradually increases. The same figure also shows that the development of folds in each bed is compensated by its extension in other places.

If the line of the profile to be depicted is drawn in the middle of the height of the advective body at any of its stages of development, the whole profile, as already stated, will be filled with folds: The zones of extension that permitted the development of the folds remain above and below the profile. Moreover, it can also be seen that the more advanced stages of development are characterized, on the whole, by more compressed folds. This is a most important property of the simple mathematical model of advection, which is the basis for the kinematic model of linear folding to be advanced here. This property must always be kept in mind in the hypotheses of the advective character of folding: The subsidence of the heavier masses and flotation of the lighter materials can lead to the development of folds without any change in width of the folded zone.

For the development of this model, one must first find criteria that can be found both in the simple mathematical model of advection and in nature (otherwise it would be impossible to compare the model with a natural folded structure). Let us consider the initial square areas of the first stage A of the advection model in Fig. 1. If they are assumed to be filled with horizontal beds, the horizontal shortening of these areas will lead to the development of a series of folds. Their axial planes will be oriented along the primary vertical side of the area, and the fold system level along the primary horizontal side. The degree of compression of the folds (the amount of horizontal shortening will be equivalent to the elongation of the primary vertical side of the initially square area (Fig. 2, *1*). These three characteristics or, as they will be called henceforth, structural criteria—the dip of the axial planes of the folds (the dip of the initially vertical side of the square area), the dip of the fold system level (the dip of the initially horizontal side of the square), and the amount of horizontal reduction or compression of the folds (the degree of elongation of the initially vertical side of the area)—are the basis for comparing the kinematic model with natural folding.

KINEMATIC MODEL OF LINEAR FOLDING: SUPERIMPOSITION OF HORIZONTAL SHORTENING ON SIMPLE MATHEMATICAL MODEL OF ADVECTION

The above-mentioned structural criteria are at the same time geometric concepts (segments of lines and angles) and permit a number of geometric (kinematic) operations: rotation in space, shift, and shortening plus elongation in mutually perpendicular directions. The formulas describing these operations can be easily derived on the basis of the assumption that the area of the figures in the kinematic operations remains constant. The kinematic operations of rotation, shift, and shortening-elongation will be described in more detail below.

A particular kinematic shortening in the horizontal direction (formal, without regard to

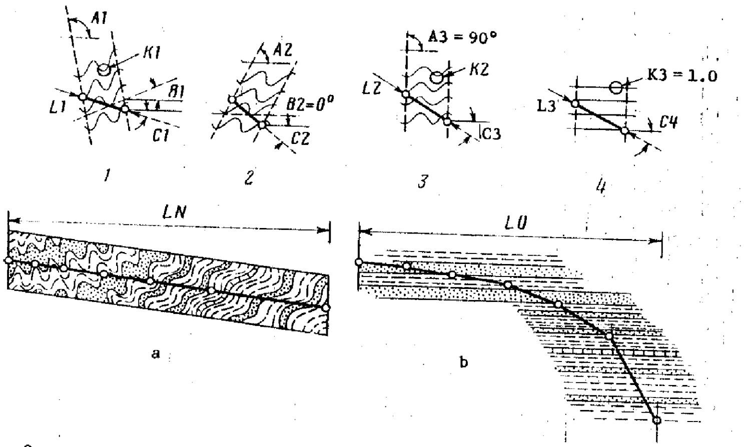

Fig. 2. Reconstruction of prefolding profile: *1-4*) change in structural criteria in kinematic operations of dip (*1-2*), shift strike-slip (*2-3*), and elongation (*3-4*); a) theoretical structural profile, b) its prefolding position.

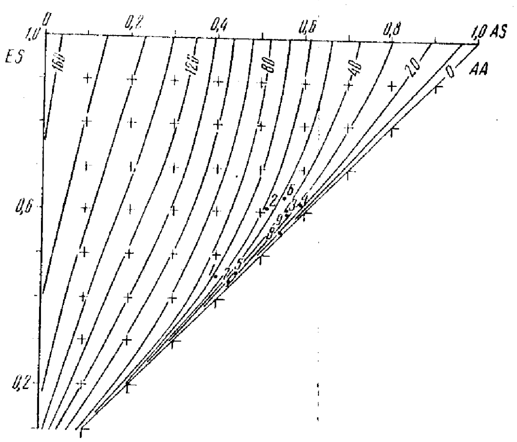

Fig. 3. Nomogram for determining amplitude of advection *AA* (lines of equal magnitude) from the computed external shortening (*ES*) and the average shortening (*AS*) of the folds along the profile. Dots and numbers next to them represent profiles across Tfanskaya zone and their numbers: 1) Fiychay R., 2) Ragdanchay R., 3) Kurvechay R., 4) Kudialchay R., 5) Agchay R., 6) Karachay R., 7) Babachay R., 8) Akhtychay R., 9) slope of Mt. Shalbuzdag.

its causes) can be superimposed not only on a separate deformed area, but also on a whole profile consisting of a multitude of such areas. This naturally leads to its reduction (transverse shortening) as a whole. Transverse shortening can, of course, be superimposed on profiles passing through the model at any stage of advection. The transverse shortening will increase the amount of the horizontal reduction of the individual folds.

The folded structure can be described by the three structural criteria, and their form determined by the advection and the distortion of this form resulting from transverse reduction can be calculated. On the basis of the advection model and the superimposed external shortening, a program for calculation on the SM-4 type computer was written. The profile across the mathematical model of advection was broken down into nine areas of folding which were considered to be homogeneous (more precisely, the inhomogeneities of each such area were averaged). In the calculations it was ascertained which average shortening or reduction *AS* (the average amount of horizontal reduction) (Fig. 3) of the folds should be observed on the profile if the advection reached the define magnitude *AA* (amplitude of advection) and the external shortening *ES* was superimposed on the advection. The advection amplitude can be measured as the angle of rotation of the initially horizontal side of the small square area whose left end is located at the immovable center of the advective cell. In Fig. 1 this center is marked by a small circle and the side of the area by a heavier line. The external shortening was taken to be the ratio of the total length of the profile after the shortening to the length it had before the shortening. In each calculation 20 versions were calculated, in which the *ES* ranged from 1 (no shortening) to 0.05 (twenty-fold shortening). The operation of calculating the average shortening of the folds *AS* is more conveniently described below. Such calculations were made for advection amplitudes from 5° to 160° at 5-20° intervals for a cell with a 1.5 ratio of its sides and the position of the profile in the middle of the cell height. The nomogram in Fig. 3 is based on the results of these calculations. In this nomogram, the average shortening of the folds along the profile is plotted on the horizontal axis and the external shortening of the profile along the vertical axis; the curves are the lines of equal amplitudes of advection. To use this nomogram, one must determine the amounts of external shortening of the profile and the average shortening of the folds. In the case of pure external shortening, these two magnitudes will coincide. In pure advection the external shortening of the profile will be equal to unity and any amplitude of advection will correspond to the average shortening AS. If the average shortening of the individual folds along the profile exceeds the external shortening of the profile, the position of the point obtained relative to the isolines indicates the amplitude of advection.

The external shortening can be determined if one performs the operation of reconstructing the profile before folding—that is, by reconstructing the position occupied in the horizontally layered (pre-folding) medium by the points through which the profile passes at the present time within the rocks buckled into folds.

RECONSTRUCTION OF PRE-FOLDING PROFILE AND DETERMINATION OF AVERAGE SHORTENING OF FOLDS ALONG THE PROFILE

The profile across the folded zone (or any model of folding) must be broken down into 10 to 20 areas, each of which should be approximately homogeneous. Each such area can be transformed by kinematic operations, returning it to its initial, pre-folding position (that is, with its beds or layers in a horizontal position and without folds). This requires three kinematic operations: 1) rotation of the area until the fold system level is in a horizontal position, 2) shifting in the horizontal direction until the axial planes are vertical, and 3) extension until the folds disappear (see Fig. 2).

These operations can be expressed by equations. To the already established structural criteria (the dip of the axial planes of the folds $A1$, the dip of the fold system level $B1$, and the amount of horizontal reduction or shortening of the folds $K1$) we add the length of the part of the profile $l1$ that dips at the angle $C1$. The operation of dip, or rotation of the fold system level to a horizontal position, will be expressed as (Fig. 2, *1-4*):

$$A2 = A1 - B1, \tag{1}$$

$$C2 = C1 - B1. \tag{2}$$

In this operation, the amount of horizontal shortening of the folds and the length of the part of the profile remain unchanged.

The next operation uses a simple shift in the horizontal direction:

$$\frac{1}{\operatorname{tg} C3} = \frac{1}{\operatorname{tg} C2} - \frac{1}{\operatorname{tg} A2}, \tag{3}$$

$$l2 = \frac{l1 \sin C2}{\sin C3}, \tag{4}$$

$$K2 = \frac{K1}{\sin A2}. \tag{5}$$

The operation of extension (elongation) can be expressed by the equations:

$$\operatorname{tg} C4 = \operatorname{tg} C3\,(K2)^2, \tag{6}$$

$$l3 = \frac{K2 l2 \sin C3}{\sin C4}. \tag{7}$$

The horizontal and vertical (lo and ho) projections of the part of the profile are:

$$lo = l3 \cos C4, \tag{8}$$

$$ho = l3 \sin C4. \tag{9}$$

By substituting the reconstructed positions of the parts of the profile for each other (Fig. 2), we obtain the pre-folding position of the profile.

For a profile with n areas we find the present line of the profile LN as the sum of the horizontal positions of all the areas. We similarly determine also the length of the pre-folding profile LO:

$$LN = \sum_{i=1}^{i=n} l1_i \cos C1_i, \tag{10}$$

$$LO = \sum_{i=1}^{i=n} lo_i. \tag{11}$$

We can then determine the amount of external shortening of the profile:

$$ES = \frac{LN}{LO}. \tag{12}$$

The average shortening of the folds along the profile AS is determined as the weighted average, using the shares of the part of the profile in the pre-folding length of the profile and the present amount of horizontal reduction of the folds:

$$AS = \frac{\sum_{i=1}^{i=n} K1_i lo_i}{LO}. \tag{13}$$

This same averaging procedure, of course, can also be used in the program of calculations from which the nomogram was constructed.

The operation of reconstructing the pre-folding profile proposed above makes it possible to reconstruct the length of the pre-folding profile if the structural criteria have been correctly measured. Estimates of the stability of the solution (in the favorable area of the nomogram) showed that the solution is stable: The introduction of 15% systematic errors into the measurements of the amount of horizontal shortening

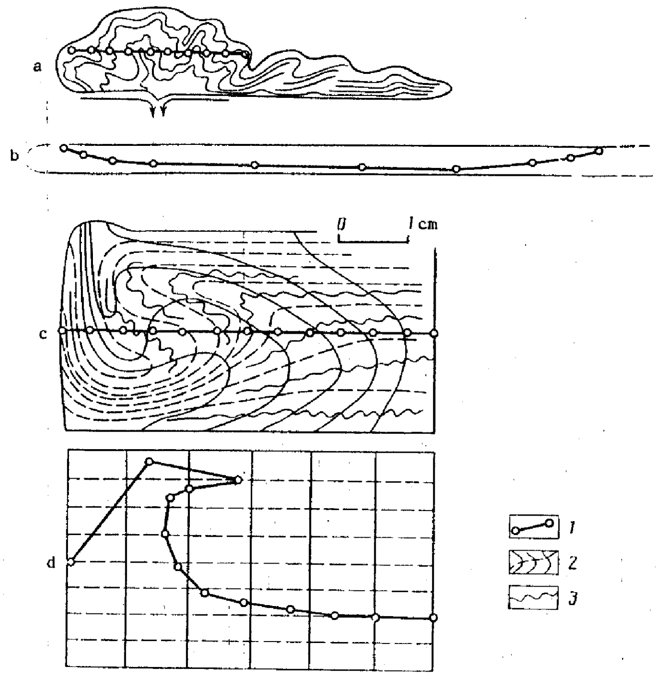

Fig. 4. Experiments in modeling of linear folding: a) experiment in compression of laminar plasticine by V. N. Larin [5], b) its profile before folding; c) M. A. Goncharov's experiment in heating of laminar resin [3], d) its profile before folding. *1*) areas of uniform folding; *2*) grid for tracking deformation (in M. A. Goncharov's experiment), in which solid lines representing axial planes of folds were initially oriented vertically, and dashed lines representing fold system levels were initially oriented horizontally; *3*) actual folds (in V. N. Larin's experiment) and their symbolic representation (in M. A. Goncharov's experiment).

of the folds reduced the external shortening of the profile and the advection amplitude by approximately the same 15%.

The method of straightening out the beds that is widely used for palinspastic reconstructions (the λ method) is considerably less precise. Figure 2 shows the part of the theoretical structural profile passing through a mathematical model of advection in which the folds were formed without any transverse shortening of the space of the advective cell. In the method of straightening out the beds, one must first draw some one bed and then measure its length and horizontal layering. The shortening of the profile thus calculated amounts to about 0.65—that is, the incorrect impression is given that the folding shown in the profile resulted from transverse shortening of the space by approximately one third. The error here lies in the incorrect extrapolation of the structure upward and downward: One cannot infer the existence of zones of extension above and below the profile directly from the observed folding. Such errors can also occur in the study of folding in nature.

STUDY OF RESULTS OF MODELING LINEAR FOLDING USING EQUIVALENT MATERIALS

Before using the proposed method on natural objects, it is desirable to test it in experiments which model linear folding. V. N. Larin's experiment in the compression of laminar plasticine [5] and M. A. Goncharov's experiment in heating a laminar resin plate [3] were chosen for this test.

The folding of transverse shortening was modeled as follows. A packet of thin laminae of modeling clay (plasticine) was attached to a sheet of paper and heated from below. The paper was then pulled through a narrow slit approximately below the center of the packet, with the result that the area occupied by the plasticine was reduced and folds were formed (Fig. 4, with movement of paper shown by arrows). Then the plasticine was cooled and transverse sections were cut through the model. From the photographs of these transverse sections, diagrams of the structural criteria were drawn (a map of the lines of equal dip of the axial planes of the folds, a map of the lines of equal dip of the fold system levels, and a map of the lines of equal horizontal shortening). In the middle part of the model, a profile consisting of the nine partial areas was drawn. The required measurements of the structural criteria in these areas were made from the diagrams thus drawn. The operations of reconstructing the pre-folding profile were then carried out, and the external shortening of the profile and average shortening of the folds were determined. The external shortening *ES* was 0.33 (or three times) and the average shortening of the folds *AS* was 0.25. The ratio of the sides of the possible advective cell is 1:8. A nomogram for this ratio of the sides of the advective cell was specially drawn and the advection amplitude *AA* was determined (15°). Thus the method of kinematic analysis enabled the experimental conditions to be correctly reconstructed: threefold shortening with little or no advection. The small manifestation of advection was probably due to the conditions of the physical experiment: shortening of the surface occurred in one place, and the modeling clay here increased repeatedly in thickness and began to spread outward in the upper part. This gravitational phenomenon was evidently detected by the method as advection.

The sample made up of resin laminae (M. A. Goncharov's experiment [3] was heated from below for several hours. The hotter lower resin layers increased in volume and became lighter than the less heated upper layers: Conditions for a density inversion arose. The lower laminae slowly floated upward, and the upper ones occupied the freed space below. After several hours the sample was cooled down and a transverse vertical section was cut through it (Fig. 4). Diagrams of the structural criteria were drawn from a photograph of this section. Then a profile consisting of 12 segments was drawn in the upper part of the model. As in the preceding case, the required measurements for these segments were taken from the maps of the structural criteria. The pre-folding profile thus constructed turned out to be of practically the same length as the profile in the sample. The average shortening of the folds *AS* was 0.41. The ratio of the sides of the square cell was 1:2. The nomograms drawn for this ratio of the sides yielded the value of 105° for the amplitude of advection. The conditions of the experiment were thereby confirmed: a complete absence of external shortening (*ES* = 1.08) and a large advection amplitude.

STUDY OF NATURAL FOLDING

Now that it has been shown that the proposed method of kinematic analysis is capable of breaking down linear folding into two components, advection and external shortening, let us attempt to apply it to folding in nature. Here it is most convenient to use the profiles drawn by Ye. A. Rogozhin and the present writer in the Tfan and Shakhdag zones of the eastern plunge of the Greater Caucasus. The methods by which these detailed profiles were drawn [6] guarantee that the structural criteria can be measured directly from the profiles. It is also important to note that the Tfan and Shakhdag zones, like the southeastern Caucasus as a whole, have served repeatedly as a test polygon for research concerning problems of the origin of folding and the laws of development of geosynclines [2, 4, 7, 8, 11].

Within the overall structure of the southeastern Caucasus, one can distinguish a series of zones, or steps, each characterized by its own particular height of uplifts, distinctive stratigraphy, history, and its own style of deformations. The Kusar, Shakhdag, Tfan, Babadag, Vandam, and Alazan zones can be discerned from north to south (Fig. 5). The southeastern Caucasus, the eastern plunging end of the Greater Caucasus meganticlinorium, is characterized by an eastward descent of the structures, which occurs mainly along several transverse flexures. The most important of these in the area of concern here are the Shakhdag and Konakhkend flexures. The rocks are variously deformed: linear folding is widespread (in the Tfan and Babdag zones and the western part of the Shakhdag zone), and box

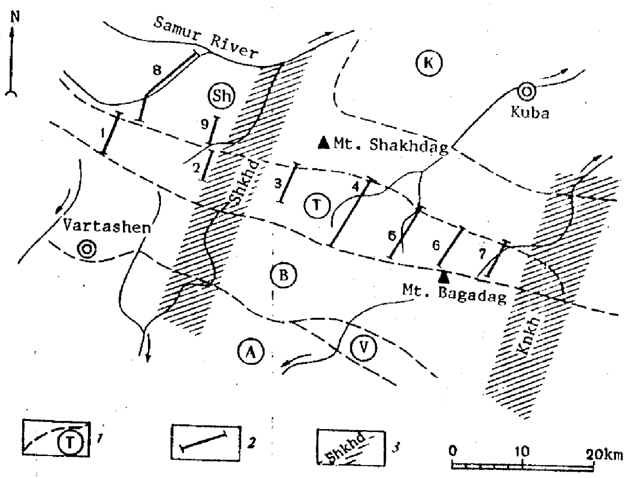

Fig. 5. Sketch map showing locations of structural profiles: *1*) boundaries of structural zones of the southeastern Caucasus (letters within circles: K) Kusar basin, Sh) Shakhdag zone, T) Tfan zone, B) Babadag zone, V) Vandam zone, A) Alazan basin); *2*) lines of structural profiles and their numbers (corresponding to numbers in Figs. 3, 6, and 7); *3*) large transverse flexures: Shkhd) Shakhdag, Knkh) Konakhkend.

and ridge-like folds also occur (in the eastern part of the Shakhdag zone and on the eastern continuation of the Babadag zone).

The oldest rocks crop out at the surface in the Shakhdag zone, where they are represented by Toarcian sandstones, siltstones, and shales with a visible total thickness of 1.5-2.0 km. The Aalenian here is made up of a shale and siltstone series containing sandstone locally. The thickness of this series is about 6 km. The section through the Middle Jurassic deposits is capped by a 300-meter band of sandstones, siltstones, and shales of Bajocian age, the top of which is eroded away. On the eroded Bajocian and Aalenian strata in the Shakhdag zone lie Upper Jurassic carbonate reef deposits, as well as Cretaceous terrigenous-carbonate series with a total thickness of 3-5 km.

In the Tfan zone are Aalenian series of shales and alternating shales and sandstones with a visible thickness of from 1 km in the east to 3.5 km in the west of the zone. These deposits on the whole are conformably overlain by massive sandstones and alternating shales and sandstones, of Bajocian and Bathonian age, and also by Upper Jurassic terrigenous-carbonate flysch, with a total thickness of 1.0-2.5 km. Southwest of Konakhkend, it can be seen that the Upper Jurassic deposits as a whole are conformably overlain by Lower Cretaceous carbonate flysch, which also occurs extensively in the Babadag zone.

The Tfan zone is bordered on the north and south by large faults—the Akhtychay fault on the boundary with the Shakhdag zone and the Malkamud fault on the boundary with the Babadag zone. In full conformity with the supposition that the linear folding in the Shakhdag zone occurred earlier (J_2/J_3) than in the Tfan zone (not before K_2?), the Akhtychay fault shows signs of long development. The Malkamud overthrust, whose displacement plane dips southward at 40-80°, as a rule separates the Upper Jurassic and Lower Cretaceous rocks in the two adjacent zones. The displacements along it may reach several kilometers. In places this fault is represented by several fractures, which together replace each other en echelon along strike.

On the profiles in the Shakhdag and Tfan zones (Fig. 6; see Fig. 5) one can clearly discern the individual folds, both large ones up to 1 km in width and smaller ones such as can be shown on the profile. Depending on the thickness of the beds, even very small folds up to a few centimeters in width can be discerned in outcrops.

In the western part of the Tfan zone (Fig. 6, *1-5*) can be seen five folds of the first rank, forming an antivergent anticlinorial structure. They consist of two synclinal folds in the marginal parts of the zone, near the Malkamud and Akhtychay faults, and also two anticlines, in turn separated by a syncline in the central part of the zone. The axial planes of these folds and also the cleavage planes dip southward in the northern anticline and northward in the anticline. In the east this structure becomes simplified, and on the profile along the Babachay River (Fig. 6, Profile 7) one can distinguish two marginal synclines and one central anticlinal fold.

The structure of the Shakhdag zone can be seen on Profile 8, supplemented by Profile 9 (Fig. 6). Here one clearly discerns two large anticlinal forms of the first rank, at respective distances of 8 and 16 km north of the Akhtychay fault, separated by a first-rank synclinal fold. Between the southern anticline and the Akhtychay fault is another large synclinal fold. The axial planes of the folds in the Shakhdag zone have no clearly discernible antivergent dip and are mainly subvertical.

Let us consider whether the proposed method of kinematic analysis can be applied to the linear folding in the Tfan and Shakhdag zones. The method can be used if the profile under study crosses a minimum of one advective cell. Turning to M. A. Goncharov's mathematical model of advection, it can be seen that besides small folds, the advective movements in each cell also form an anticline and a syncline of the first rank, and combined adjoining cells (two of which can be seen in Fig. 1) represent an alternation of anticlinorial and synclinorial forms. These anticlinorial and synclinorial structural forms in the mathematical model of advection are comparable to the folds of the first rank described in the Tfan and Shakhdag zones. Consideration of the structures of these zones from this standpoint showed that from two to four advective cells can be discerned in the Tfan zone and four such cells in the Shakhdag zone (Fig. 6).

For a correct determination of the amplitude of advection, it is important to know the ration of the vertical and horizontal sides of these inferred advective cells. In the Tfan zone the total thickness of the geosynclinal deposits visible on the profiles reaches 3-5 km; in the Shakhdag zone the visible thickness of the Middle Jurassic deposits is about 8 km. The exact thickness of the geosynclinal series here is not known, but it can be supposed that the unexposed part of the section does not exceed a few kilometers in thickness. The average width of the advective cell (the pre-folding length of the cell along the profile) is 6-8 and 10.5 km, respectively. The ratio of the sides of the advective cells in these zones is thus less than 1.3-2.0; therefore, to the first approximation, for estimating the ratio we can use the value of 1.5 adopted in M. A. Goncharov's mathematical model of advection (Fig. 1), and the amplitude of the advection was determined from the nomogram drawn for this ratio (Fig. 3).

The structure of each profile was divided into a series of areas of uniform folding, and from three to six such areas were distinguished within each advective cell discerned. This was less than in the calculated model used, but had almost no effect on the accuracy of the analysis: Special calculations showed that a decrease in and ridge-like folds also occur (in the eastern part of the Shakhdag zone and on the eastern continuation of the Babadag zone).

The oldest rocks crop out at the surface in the Shakhdag zone, where they are represented by Toarcian sandstones, siltstones, and shales with a visible total thickness of 1.5-2.0 km. The Aalenian here is made up of a shale and siltstone series containing sandstone locally. The thickness of this series is about 6 km. The section through the Middle Jurassic deposits is capped by a 300-meter band of sandstones, siltstones, and shales of Bajocian age, the top of which is eroded away. On the eroded Bajocian and Aalenian strata in the Shakhdag zone lie Upper Jurassic carbonate reef deposits, as well as Cretaceous terrigenous-carbonate series with a total thickness of 3-5 km.

In the Tfan zone are Aalenian series of shales and alternating shales and sandstones with a visible thickness of from 1 km in the east to 3.5 km in the west of the zone. These deposits on the whole are conformably overlain by massive sandstones and alternating shales and sandstones, of Bajocian and Bathonian age, and also by Upper Jurassic terrigenous-carbonate flysch, with a total thickness of 1.0-2.5 km. Southwest of Konakhkend, it can be seen that the Upper Jurassic deposits as a whole are conformably overlain by Lower Cretaceous carbonate flysch, which also occurs extensively in the Babadag zone.

The Tfan zone is bordered on the north and south by large faults—the Akhtychay fault on the boundary with the Shakhdag zone and the Malkamud fault on the boundary with the Babadag zone. In full conformity with the supposition that the linear folding in the Shakhdag zone occurred earlier (J_2/J_3) than in the Tfan zone (not before K_2?), the Akhtychay fault shows signs of long development. The Malkamud overthrust, whose displacement plane dips southward at 40-80°, as a rule separates the Upper Jurassic and Lower Cretaceous rocks in the two adjacent zones. The displacements along it may reach several kilometers. In places this fault is represented by several fractures, which together replace each other en echelon along strike.

On the profiles in the Shakhdag and Tfan zones (Fig. 6; see Fig. 5) one can clearly discern the individual folds, both large ones up to 1 km in width and smaller ones such as can be shown on the profile. Depending on the thickness of the beds, even very small folds up to a few centimeters in width can be discerned in outcrops.

In the western part of the Tfan zone (Fig. 6, *1-5*) can be seen five folds of the first rank, forming an antivergent anticlinorial structure. They consist of two synclinal folds in the marginal parts of the zone, near the Malkamud and Akhtychay faults, and also two anticlines, in turn separated by a syncline in the central part of the zone. The axial planes of these folds and also the cleavage planes dip southward in the northern anticline and northward in the anticline. In the east this structure becomes simplified, and on the profile along the Babachay River (Fig. 6, Profile 7) one can distinguish two marginal synclines and one central anticlinal fold.

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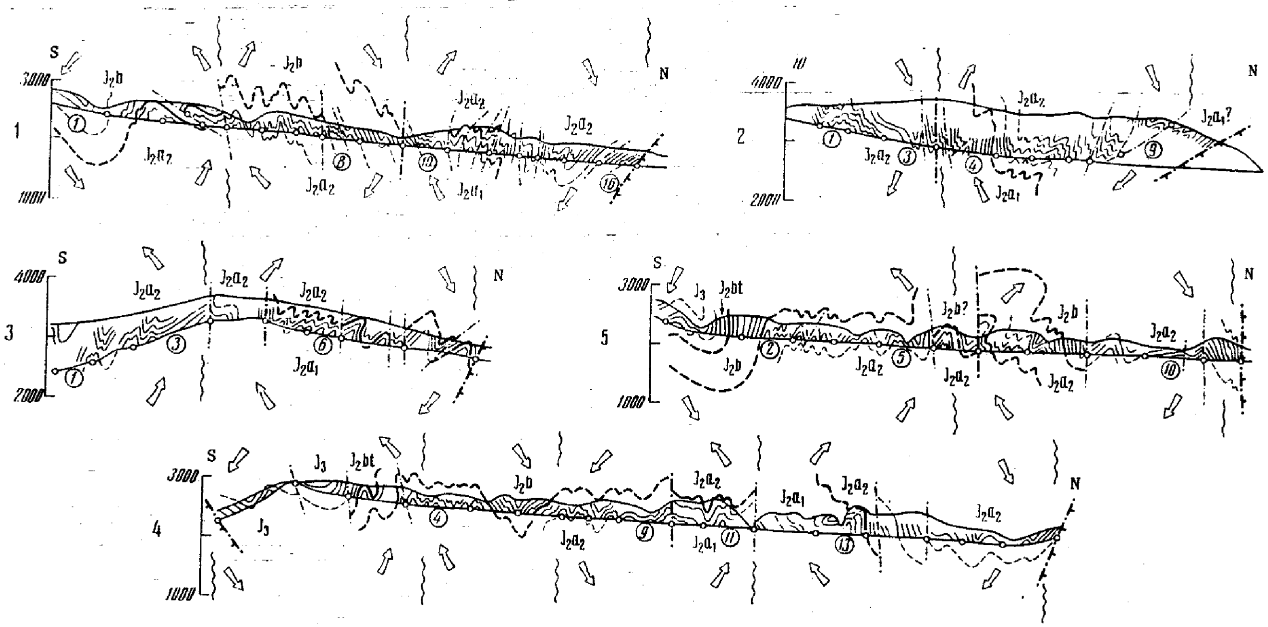

Fig. 6 (I)

Fig. 6. Structural profiles across the Tfan and Shakhdag zones in the southeastern Caucasus (prepared by Ye. A. Rogozhin and F. L. Yakovlev): *1*) structural lines: a) boundaries of stratigraphic units, b) individual strata with lithology not indicated; *2*) fractures: a) of small, b) of considerable amplitude, c) faults serving as boundaries of zones: Akhtychay in north of profiles (except 9th) and Malkamud in south; *3*) profile numbers, corresponding to those in Figs. 3, 5, and 7; *4*) boundaries of known areas of homogeneous folding and their numbers (shown selectively); *5*) inferred advective cells: a) cell boundaries, shown roughly, b) inferred directions of advective movements.

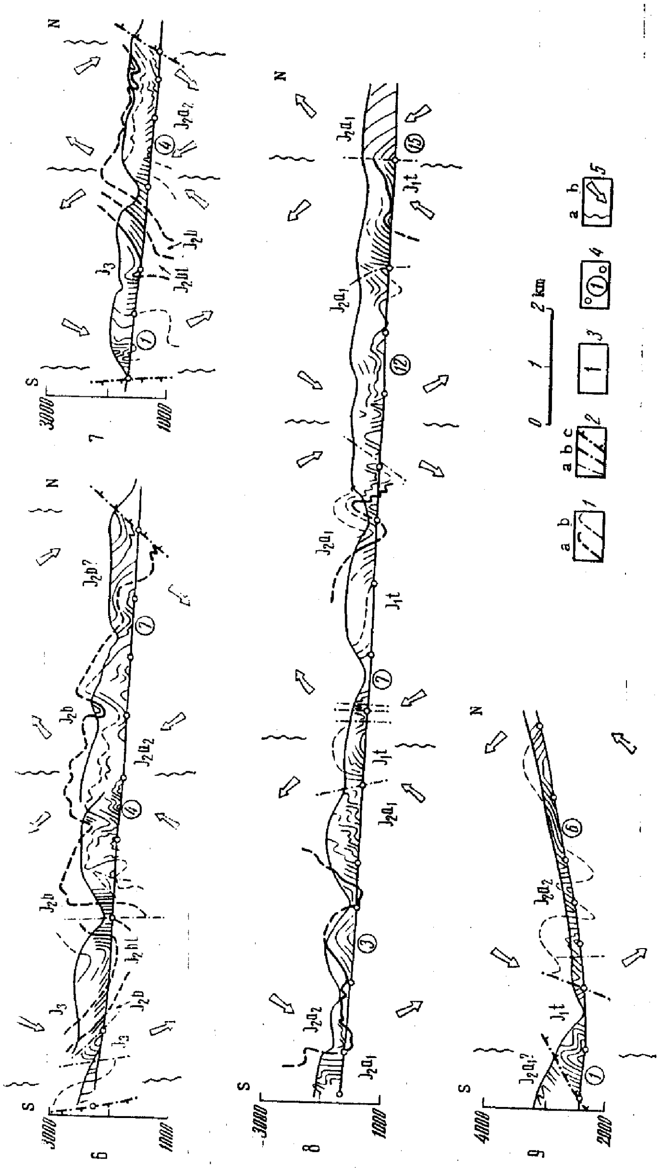

Fig. 6 (II)

number of uniform areas from 10 to 3 can change the advection amplitude by no more than 7-10%.

As an example, let us look at the processing of the structural materials on the profile along the Fiychay River (Profile *1* in Fig. 6). Here 16 areas were distinguished. The dip of the axial planes of the folds were measured in each area. If there was more than one fold, the average dip was determined. Then the dip of the fold system level was measured. For this purpose, usually, some one bed in the area of the profile was extended to the boundaries of its area and the beginning and end of the bed were then joined by a straight line. The dip of this straight line gave the angle of orientation of the fold system level. The subvertical fractures breaking up the folded structure were generally considered to be the boundaries of the areas of uniform folding, and as such did not hinder the measurements. If any such fractures were located within an area, the measurements were made on the same bed between these fractures, and the average angle of dip of the fold systems levels was then found. The amount of horizontal reduction was determined as the angle of convergence of the fold flanks α by the formula $K = \sin(\alpha/2)$. If there were several folds within an area, the amounts of horizontal shortening of the folds were averaged. In principle, it is desirable to use more precise methods in estimating the amount of horizontal reduction of the folds [12, 13]. But observations of the change in thickness of the sandstone beds in the fold hinges within the area under study and of certain other features showed that the use of the above formula does not lead to excessive errors. The length of the area in the direction chosen (along the water's edge, as a rule) and the angle of dip of this line were also measured. After the data on the structural criteria for all 16 areas were collected, calculations were made by Formulas (1) to (9) above, and their results (Table 1) made it possible to calculate the length of the pre-folding profile and to determine the average shortening of the folds, the external shortening of the profile, and the amplitude of advection.

In the same manner, the data on the other profiles were gathered and the amounts of external shortening and the advection amplitudes were calculated (Fig. 3; Table 2). Below (I-III) are the initial measurements of the structural features on the objects of linear folding.

The external shortening for the Tfan and Shakhdag zones turned out to be from 0.439 to 0.633 (that is, the structure was reduced transversely 2.28 to 1.58 times), and the advection amplitudes ranged from 68° to 20°. It can be seen from the Table that in the case of natural folding, the method of kinematic analysis revealed considerable magnitudes of both advection and external shortening.

DISCUSSION OF RESULTS

The results of the kinematic analysis of all the objects studied were plotted on a graph (Fig. 7), in which the kinematic external shortening (1/*ES*) was laid out along the horizontal axis, showing how many times the length of the profile has been shortened, regardless of the cause, and along the vertical axis the amplitude of advection—that is, the kinematic magnitude indicating how far the advection process has gone.

Table 1

Analysis of Structural Material on the Profile Along the Fiychay River

Area No.*	Structural criteria (Formulas 1 - 9)						
	l_1, m	C_1, deg	A_1, deg	B_1, deg	K_1	l_0, m	h_0, m
1	960	—14	113	2	0,39	1965,9	—110,5
2	910	—6	120	80	0,55	1330,0	—777,2
3	785	—7	120	—12	0,42	1492,7	38,7
4	595	—18	129	—21	0,48	675,1	29,9
5	610	—5	107	—21	0,38	1490,5	80,9
6	570	—6	90	—22	0,25	2267,5	42,4
7	460	—6	94	—34	0,60	755,0	163,4
8	640	—6	90	—32	0,29	2193,1	96,4
9	760	—4	90	—70	0,36	2105,2	741,5
10	785	—5	91	—26	0,70	1115,3	221,0
11	660	—4	77	1	0,35	1862,5	—20,8
12	525	—3	60	—72	0,34	1375,8	222,2
13	305	—5	54	—52	0,54	484,1	125,3
14	480	—3	60	—60	0,40	1069,2	185,9
15	575	—4	68	32	0,48	1139,3	—276,0
16	665	—2	50	43	0,38	1379,0	—1446,2

*Areas numbered from N to S; area No. 16 extends to the Akhtychay fault.

Table 2

Results of Kinematic Analysis of Folding in the Tfan and Shakhdag Zones

Basic criterion	Profile No.								
	1	2	3	4	5	6	7	8	9
No. of areas of uniform folding	16	9	8	17	11	8	6	16	7
Present length of profile, m	10 192	5995	7 329	14 446	9 664	10 030	5 474	19 922	6 394
Length of pre-folding profile, m	22 692	9895	12 220	23 436	21 116	15 833	12 470	36 093	10 675
External shortening of profile	0,449	0,606	0,600	0,616	0,458	0,633	0,439	0,552	0,599
Average shortening of folds along profile	0,400	0,516	0,560	0,596	0,444	0,557	0,427	0,543	0,563
Amplitude of advection	68	58	37	25	37	47	37	20	35

Area No.	I											
	1	2	3	4	5	6	7	8	9	10	11	12
$A1$	85	140	262	220	185	158	145	141	142	142	133	100
$B1$	−88	+120	+160	+161	+133	+100	+68	+42	+30	+12	+7	+3
$K1$	0,40	0,23	0,60	0,90	1,20	1,00	0,80	0,52	0,38	0,45	0,54	0,62

[1] M.A. Goncharov's model; in all areas $l1$ = 5 mm, Cl = 0.

Area No.	II								
	1	2	3	4	5	6	7	8	9
$A1$	150	145	140	110	80	60	80	42	55
$B1$	+60	+60	+50	+20	+1	−15	−20	−33	−40
$K1$	0,45	0,37	0,30	0,18	0,18	0,19	0,25	0,38	0,50

[2] V. N. Larin's model; in all areas $l1$ = 3 mm, Cl = 0.

Area No.	III																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
$l1$	1450	900	1000	1145	800	745	440	550	970	525	865	1040	890	1010	660	730	930
$C1$	+25	−13	−9	−5	−5	−5	−5	−4	−4	−4	−4	−1	−1	−1	−2	−4	+9
$A1$	110	105	105	107	92	70	80	70	75	68	78	58	70	78	81	70	83
$B1$	+7	+22	+50	−13	−55	+45	−10	−5	+10	−28	+16	−47	−33	−70	−31	−22	+18
$K1$	0,79	0,63	0,52	0,46	0,50	0,65	0,70	0,34	0,61	0,87	0,62	0,63	0,64	0,47	0,78	0,64	0,79

[3] Profile No. 4, Kudialchay River.

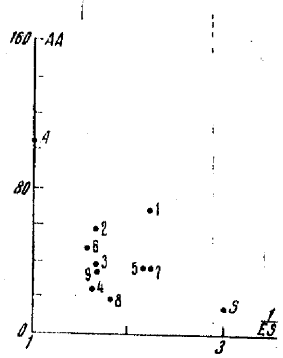

Fig. 7. Graph comparing results of kinematic analysis of natural and experimental linear folds. Numbered points represent profile numbers.

V. N. Larin's external shortening experiment (Point S) is far from the advection axis and close to the axis of shortening. This position of Point S indicates that the leading process in this experiment was external shortening. M. A. Goncharov's advection experiment (Point A) lies exactly on the vertical axis of advection; this shows that here advection was the only process forming the structure obtained. Points 1-9, corresponding to the numbered profiles across the Tfan and Shakhdag zones of the southeastern Caucasus, are clustered in a group approximately equally distant from both axes. From this position of the numbered points, it must be concluded that neither pure external shortening nor pure advection alone could have formed the structures under study. But the combination of both processes from the kinematic point of view can yield a satisfactory explanation and interpretation of the folding in this region.

The question arises: Can external shortening somehow be transformed into movements equivalent to advection, as probably happened in V. N. Larin's experiment? If so, the natural structure could be attributed to external shortening alone, although it would have been somewhat more complicated. A direct, precise answer to this question cannot be given, but certain suppositions are suggested by indirect estimates.

Before proceeding, let us consider the relationship between the values obtained for the external shortening and advection. If advection results from external shortening, one would expect to find some direct functional relation between them in which a growth of external shortening causes or is caused by an increase in advection. In statistics, a relation is considered functional if the correlation coefficient is above 0.7, and the closer it is to 1.0, the stronger the manifestation of this function. The correlation coefficient calculated for these nine profiles (r = -0.21) shows that such a relationship is absent—that these values are independent.

Now let us attempt to estimate, if only qualitatively, the contributions made separately by external shortening and advection to the property of folding that is usually called its intensity, stress, or morphological complexity [7]. Let us compare the paired profiles 1 and 5, 2 and 4, which differ in advection amplitude but are equal in the amount of their external shortening. The folding in Profiles 1 and 2, where the advection amplitude is higher, looks more complicated and stressed, and that on Profiles 5 and 4 simpler and less intense, indicating an increase in morphological complexity of the folding with a growth of advection (Fig. 6). If one compares profiles that differ in external shortening but are the same in amplitude of advection, such as 5 and 3 and also 7 and 9, for example, it is hard to decide which of the pair is the more stressed, indicating that the morphological complexity is independent of external shortening. Quantitative estimates made of these relationships (the procedures of which we cannot consider here) support the conclusion: The coefficient of correlation between the morphological complexity of the folding and the advection amplitude is 0.69 (that is, the relationship between them is close to functional), whereas in the case of external shortening the coefficient is -0.21 (that is, there is no correlation).

Thus it turns out that the very same amount of external shortening can be accompanied by the development both of simple, not very stressed folding consisting of large relatively undisturbed folds and of intense folding consisting of a large number of small, highly stressed folds. The complexity or stress of the folding depends on the process that is registered by the proposed method as kinematic advection. As was shown above on the basis of indirect evidence, this advection can in no way be the result of external shortening, but is a fully independent process.

V. N. Sholpo [10], in substantiating the hypothesis of subsurface diapirism at depth (advection) on Greater Caucasus materials, pointed out a number of features that should be typical of advective structures. These include, above all, the two-humped fan-like general form of the structure, in which two large, relatively stressed anticlines have their axial planes dipping toward each other and are separated by a syncline or graben and bordered on their outer margins by two equally large but relatively simple synclines. Examples of such structures are the Svanetian anticlinorium and the flysch synclinorium on the southern slope of the Greater Caucasus. As can be seen from the profiles and descriptions of the folding, the structure of the Tfan zone has just such an advective form.

A second feature of advective folding is the development of metamorphism leading to the development of aspidic shales and cleavage, which in V. N. Sholpo's opinion indicate decompaction of the material, a requirement of advection. The clay rocks of the region under study have gone through the necessary initial metamorphism, and cleavage can be discerned in them, most strongly manifested in the areas of Profiles 1 and 2—just where the greatest advection amplitudes were found. Thus, according to both known characteristics, an advection process must have occurred in the area studied, once again confirming the conclusion that this process took part in forming the structure under study.

It would seem that an exact answer to the question of the relationship of advection to external shortening could be obtained by a series of experiments on equivalent materials, in which a series of strata with a density inversion changing from one experimental run to the next is subjected to the same amount of external shortening. A study of the kinematics of these experiments and their comparison with natural objects may reveal whether advection caused by density inversion takes part in the folding. The performance of such experiments will require improvements in both experimental instrumentation and technique. The traditional physical modeling of folding with the participation of only some one process, of course, is important in studying the distinctive character of the structures formed, but the results of such modeling, as the graph in Fig. 7 shows, are far from nature.

The process of external shortening or reduction likewise seems to be quite real. A shortening of the profiles by an average factor of two, when the cover of sedimentary rocks is 6-8 km in thickness and the initial width of the zone is 20-30 km, cannot fail to affect the geosynclinal basement. As M. L. Somin points out [8], in many parts of the area of passes in the western Caucasus Main Range, intense folded deformations have been described that have affected both the slightly metamorphosed Jurassic deposits and the rocks of the pre-Jurassic crystalline basement.

The proposed kinematic analysis of linear folding, as we have seen, can help to solve certain important problems of the mechanism and mechanics of linear folding. It must be understood, however, that this method can hardly explain all the basic aspects of this extremely complicated problem. The two characteristics dealt with here—the amount of external shortening and the amplitude of advection—do not exhaust the whole variety of possible manifestations and other mechanisms of folding, particularly the block movements of the geosynclinal basement and the sliding of rocks down the slopes of tectonic uplifts. These limitations of the method prevent extensive application of the results obtained here: It is too early, for example, to draw any conclusions of geotectonic character from them. This compels one to strive for improved methods of kinematic analysis such as may reveal more mechanisms of folding.

CONCLUSIONS

1. A method of kinematic analysis of linear folding is proposed on the basis of models combining two processes of folding—advection, in which the development of folds requires no external shortening. The method advanced enables these two components to be distinguished quantitatively in any objects of linear folding. The method uses structural criteria (the dip of the axial planes of the individual folds, the dip of the fold system level, and the amount of horizontal shortening of the folds) that can be measured both in natural structures and in experimental models. The procedures for processing the data are the same for any objects, enabling these objects to be compared with each other on the basis of the results obtained—the amplitude of advection and the amount of external shortening.

2. The analyses of V. N. Larin's experimental model of external shortening and of M. A. Goncharov's advective experimental model to test the proposed method have shown that the method does indeed permit distinguishing the advective component of folding from the component of external shortening.

3. The study of the linear folding in the southeastern Caucasus by the proposed method has shown the considerable magnitudes of both these components. This means that neither pure external shortening nor pure advection by itself alone could have formed these structures, but that some combination of these processes can explain the folding in this region.

4. Study of the quantitative correlations between the estimated external shortening and the amplitude of advection, as well as their separate relationship to the stress or intensity of the folding, has shown the independence of the advection process from the external shortening of the structure and also its reality.

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