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V.S. Burtman

This article will discuss a method of historical-tectonic analysis of folded complexes that is based on the results of structural-geologic investigations. The method consists of two parts, the first of which is fully independent.

I. ANALYSIS OF THE STAGES OF FOLDING

A historical-tectonic analysis of folding often seems to be complete when it has revealed the style of the folding, and its age, as established by the angular unconformities, has been determined as belonging to one or several stratigraphic gaps – phases of folding. Yet the folding process within each of the phases of folding thus detected shows considerable changes whose succession can be deciphered by analyzing the folded structure of the tectonic zone. This succession can be established when either the structural forms arising in different stages of the folding process or their orientation are different.

For the purposes of such analysis, folded structures can be divided into three types, in each of which the orientation of the main axes of deformation is in principle different. The three types are: vertical folds with steep axial planes and gently sloping hinges, horizontal folds with steep hinges, and recumbent folds whose hinges and axial planes are both gently sloping (Burtman, 1968). The appearance of folds belonging to one type or another is determined by the orientation of the principal stress axes. Thus, for example, in the formation of a vertical fold in longitudinal bending, the direction of the maximum compressive stress is horizontal, and that of the minimum compressive stress vertical. For the formation of horizontal folds, the stress in any horizontal direction must be less than the gravitational forces. Such conditions arise in horizontal displacements within the earth's crust – for example, along strike-slips, with which horizontal folds are often combined (Peyve, 1960; Burtman, 1964). Recumbent folds are associated with thrusts and nappes, and vertical folds with faults of all types. Within each of these associations, its members may alter and replace one another. Thus the formation of vertical, horizontal and recumbent folds involves different processes of folding, each of which is characterized by specific dynamics, kinematics and structural associations. The conditions under which each of these types of folds are formed are so different that as a result, each stage of folding in a particular structural zone is characterized by the predominance of folded structures of one type or another. As an example, we shall consider the stages of folding in tectonic zones with folding of different ages, but with the same tendency characterizing the folding process.

In the Caledonian areas of the Grampian highlands of Scotland, the folding processes began after the geosynclinal sedimentation had come to an end. A system of thrust sheets was formed in the first stage. The thrust sheets of the Grampian highlands, made up of Upper Precambrian and Cambrian rocks, form a cascade of recumbent folds. The lower thrusts are large recumbent synclines complicated by overthrusts, while the upper thrust sheet is interpreted as a double recumbent fold. Numerous small recumbent folds arose at the same time as the large folds were formed. The orientations of the folds belonging to the first stage is northeast. During the following stage, small compressed vertical folds of northwest orientation were formed in the Grampian highlands. The folded structures arising in the third stage are large open vertical folds whose axes have roughly east-west orientations. In the fourth stage were formed small vertical folds of northeast orientation, and in the fifth stage – horizontal folds associated with strike-slips. Several stages of metamorphism combined with the stages of folding have been established in the Caledonides of northern Scotland. The available absolute-age determinations of the metamorphism suggest that the interval between the second and third stages of folding was several tens of millions of years long (Bailey, 1950; Brown et al., 1965; Johnson, 1965; Johnstone, 1965; Rast, 1963; Weiss and McIntyre, 1957).

In the Variscides of the southern Tien Shan region, the formation of the folded structures began at the end of the Middle Carboniferous, after the geosynclinal sedimentation had ended. In the first stage eugeosynclinal Middle Paleozoic rocks were overthrust upon the miogeosynclinal formations in the form of vast thrust sheets. Numerous recumbent and compressed S-shaped folds arose in the allochthone of the thrust sheets. Thereafter the thrust sheets were broken by faults and in places slightly deformed into gentle vertical folds. These movements may be regarded as constituting the second stage. The third stage of folding developed after the accumulation of the Upper Carboniferous molasse. In this stage the allochthone and autochthone were compressed with the molasse into

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vertical folds, the largest of which can be traced for some tens of kilometers. During the fourth stage in the area of the Fergana range and the eastern Alay region all the earlier formed structures were collected into large horizontal folds and broken by strike-slip faults (Burtman, 1968).

The following succession of folding processes has been found in the zone of Mesozoic folding in New Zealand. In the first stage, in the Late Paleozoic and Mesozoic geosynclinal rocks a system of recumbent folds and thrust sheets was developed in the New Zealand Alps and the province of Otago. In the second stage vertical folds appeared and the New Zealand anticlinorium and its accompanying synclinorium were formed. To the third stage belongs the formation of the New Zealand horizontal flexures, horizontal folds and movements along strike-slips (Burtman, 1965).

In the areas of the central and southeastern Pamirs the Alpine processes of folding began at the end of the Cenozoic, after the end of the geosynclinal and orogenic sedimentation. In the first stage of the folding process here, the Mesozoic and Cenozoic deposits of the central Pamir region were torn away from their Paleozoic basement and gathered into large recumbent folds accompanied by thrusts. Then, after regional metamorphism, over these rocks were thrust nappes, thereby forming a multilayered system made up of Paleozoic and Mesozoic-Cenozoic rocks. In the course of this thrusting, recumbent folds were formed in the allochthone. Even during the formation of the system of thrust sheets, the tectonic plates were deformed along with the formation of gentle horizontal folds. These deformations continued, and subsequently led to the buckling of the thrust sheets into vertical folds. In the following stage, strike-slip movements took place along faults, accompanied by the development of horizontal folds (Ruzhentsev, 1968).

All the regions of the world considered above, despite the different numbers of their stages of folding, were characterized by the same tendency of the part of the folding process. The formation of the folded structures began with the appearance of recumbent folds and thrust sheets. Vertical folds arose in step II. Step III saw the formation of horizontal folds and strike-slip faults. Several stages could be distinguished within step II because of the successive change with time in the orientation of the principal stress axes relative to the cardinal points of the compass. Consideration of the above examples shows that in a number of cases these steps were separated by prolonged intervals of time. Such an interval occurred between step I and II in southern Tien Shan, encompassing the Late Carboniferous epoch. Considerable intervals may also have come between steps II and III in southern Tien Shan, steps I and II in New Zealand, and all the steps in Scotland. On the other hand, the example of the Pamir indicates that the formation of the folds belonging to a new step may begin even before the end of the preceding step. In the examples cited, it is also worth noting that the development of the folding processes proceeded in the same direction, regardless of the particular stage of geosynclinal development in which the folding began in a given tectonic zone.

II. THE SUCCESSION OF TECTONIC REGIMES OF DEFORMATION

The tectonic regime existing at a definite stage of the tectonic process within one geologic body or another (tectonic block, zone, system, etc.) is determined by the character of the deformation of that body. The concept of a tectonic regime, in the sense in which it is understood here, was first introduced by W. B. Harland (1956) and M. B. Bailey (Harland and Bailey, 1958). There are two aspects of the concept of tectonic regimes to be considered. On the one hand, these are tectonic regimes of deformation; on the other hand, they are tectonic regimes of stress. In an ideally elastic isotropic body the relationships between the magnitudes of the stress and of the deformation, or strain, will be proportional. In actual geologic bodies these relationships are, of course, more complicated and are almost never known precisely. Harland and Bailey proposed a system of analysis of the stresses proceeding from an assumption of ideal relationships between the deformations and the stresses. But attempts to use this sytem in the analysis of concrete materials encounter great difficulties. How, for example, is one to find out which of the stresses was the greatest: the stress that led to the overthrusting of the nappe, or the stress that caused the formation of the vertical folds? It seems more rational, therefore, to concentrate on analyzing the actual deformations of the geologic objects: the amount and direction of the deformation can be estimated by using the materials of structural-geologic investigations. The anisotropy of geologic bodies is the reason for the considerable variety of structural forms arising from the action of one and the same system of stresses. In striving toward a clear, unequivocal estimate, as the requirement of a universal system, we will take into account only the main result of the deformation, as expressed in the change in the volumetric relationships within the body under consideration (that is, its elongation and shortening and their directions), regardless of whatever particular structural result (folds, thrusts, grabens, etc.) may be achieved by the deformation.

Below is described a system consisting of the 48 tectonic regimes of deformation that can theoretically arise in the deformation of a geologic body without any change in its volume. The existence of any of these regimes in the geologic body to be analyzed and the succession of regimes can be determined from the results of structural analysis, which must meet the following requirements: it must 1) identify the stages of folding like those described in the preceding section of this article, and determine the succession of these stages; and 2) for each stage, discover the directions of shortening and elongation of the geologic body under consideration. If the elongation (or shortening) has been in two directions, it must be ascertained whether it was the same in both directions, or whether the deformation in one of the directions predominated. It must be stressed that the use of this method does not require finding the absolute magnitudes of the shortening or elongation, which in many cases will be difficult or impossible. It is enough to find out in which direction the deformation was greater and in which direction it was less.

To explain the constructions to follow, let us turn to the simplest model. If a sphere[1] is subjected to deformation in three dimensions, in the most general case it is transformed into a triaxial deformation ellipsoid, whose mutually perpendicular axes constitute the principal strain axes x, y and z. The directions of these axes correspond to the directions of the principal stress axes, and the orientation of the latter in turn depends on the directions of the external forces. In the tectonic process, the direction of one of the forces (the earth's gravitation) is constant. If the z axis is parallel to the direction of the gravitational force (that is, vertical), the x and y axes will lie in the horizontal plane. Let us therefore orient the x axis parallel to the direction of the first horizontal shortening or compression of the geologic body under consideration. Then the y axis will extend parallel to the axes of the folding structures that arose in the course of this deformation.

The relationships between the magnitudes of the axes of the deformation ellipsoid and their change relative to their initial magnitude (elongation or shortening) determine the 24 tectonic regimes that are possible in the given system of coordinates. Let us mark the axes that have been shortened as a result of the deformation by the lower-case letters x, y and z, the axes that have become longer by the capital letters, X, Y and Z, and the axes that remained unchanged with the symbols $\mathring{x}$, $\mathring{y}$ and $\mathring{z}$. The relationships between the axes of the ellipsoid of deformation can be conveniently depicted in the form of a ternary diagram. The point of the center of the triangle (fig. 1) characterizes the undeformed imaginary sphere ($\mathring{x} = \mathring{y} \quad \mathring{z}$). All the remaining points in the triangle correspond to ellipsoids that have different relationships between their axes. Let us draw the straight line ab through all points for which $z = \mathring{z}$; it will pass through the center of the triangle and run parallel to the

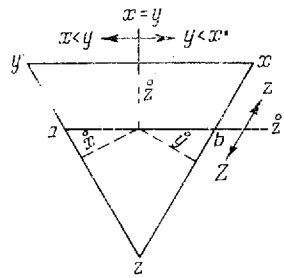

FIGURE 1
(Explanation in text)

side yx. This straight line divides the diagram into two fields. In the upper field are ellipsoids whose vertical axes have been shortened, and in the lower field the ellipsoids whose vertical axes have become longer. The median of the angle z divides the triangle into two halves, so that in the right half y < x, in the left half x < y and, for all points lying on the median, x = y. If we also draw lines for all three coordinates, we obtain a diagram (fig. 2) consisting of 12 fields and 12 lines separating them. This diagram graphically illustrates 24 tectonic regimes of deformation – the 24 possible variants of the mutual relations between the principal strain axes. The characteristics of these relationships are summarized in the Table (column 2).

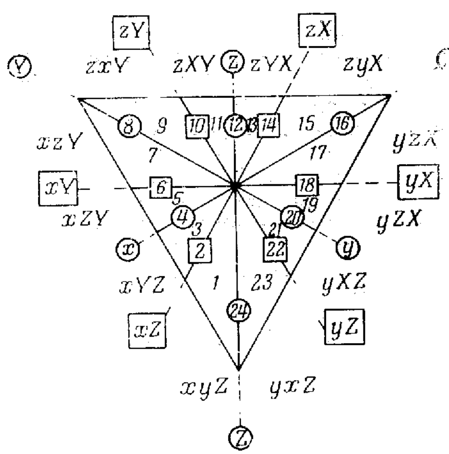

FIGURE 2. Tectonic regimes of deformation

It is inconvenient to use expressions of inequality, so that the third column of the table contains proposed symbols for the regimes of deformation which are briefer and yet include full information on the character of the deformations in each regime. The regimes under consideration are of three kinds. In regimes of the first kind (Nos. 2, 6, 10, 14, 18, 22) the shortening along one axis is fully compensated by elongation along another, while the third axis

[1] This refers to an imaginary element of the body to be analyzed, which had a spherical form before the deformation.

remains unchanged,[2] – that is, the deformation takes place in one plane. These are the main regimes of deformation in the tectonic process. To characterize such regimes it is sufficient to indicate the axes that have undergone change: xZ-regimes, zX-regimes, xY-regimes and so forth.[3]

In regimes of the second kind (Nos. 4, 8, 12, 16, 20, 24) the shortening or elongation along one axis is compensated by equal changes along the two other axes. To designate the regimes of the second kind, it is sufficient to indicate the axis along which the principal shortening or elongation has taken place: x-regime, X-regime, y-regime, etc. The remaining regimes of deformation are characterized by changes of equal magnitude along all three axes. In the designations of the regimes of this third kind, the symbols for the axes will be placed in increasing order – from the most shortened axis to the most elongated: xyZ-regime, xYZ-regime, etc. The use of this system, consisting of 24 regimes of deformation in one system of coordinates, is a convenient aid in detailed tectonic and comparative tectonic analysis. If a more general approach is called for (or there is an insufficiency of data), one can use a system of six main regimes of deformation, which are indicated in the accompanying Table (column 4) and on a diagram (fig. 3). This variant neglects the effect of the deformation along the axis that has undergone the least change.

The right-hand column (column 5) of the Table shows the groups of regimes, designated by the symbol for the axis that has undergone the most shortening. The tectonic significance of these groups is as follows. The group of x-regimes characterizes the conditions of formation of the structural forms arising as a result of primary horizontal compression. The group of z-regimes indicates the formation of structures of horizontal extension, gravity-flow structures and structures of vertical discharge of load. The group of y-regimes are those charactering the formation of structures as a result of repeated horizontal compression oriented at right angles to the primary horizontal compression.

The purpose of the investigation is to learn the succession of tectonic regimes of deformation during the time of a tectonic cycle. For this purpose, the capacities of the system considered above are not sufficient: one can readily imagine conditions of deformation whose

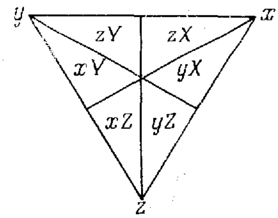

FIGURE 3. Main tectonic regimes of deformation

Table of tectonic regimes of deformation

Number of regimes on diagram	Ratios of principal strain axes	Index of regime	Main regimes	Groups of regimes
1	2	3	4	5
1	$x < y < Z$	xyZ		
2	$x < \mathring{y} < Z$	xZ	xZ	
3	$x < Y < Z$	xYZ		
4	$x < Y = Z$	x		x
5	$x < Z < Y$	xZY		
6	$x < \mathring{z} < Y$	xY	xY	
7	$x < z < Y$	xzY		
8	$x = z < Y$	Y		
9	$z < x < Y$	zxY		
10	$z < \mathring{x} < Y$	zY	zY	
11	$z < X < Y$	zXY		
12	$z < X = Y$	z		
13	$z < Y < X$	zYX		z
14	$z < \mathring{y} < X$	zX	zX	
15	$z < y < X$	zyX		
16	$z = y < X$	X		
17	$y < z < X$	yzX		
18	$y < \mathring{z} < X$	yX	yX	
19	$y < Z < X$	yZX		
20	$y < Z = X$	y		
21	$y < X < Z$	yXZ		y
22	$y < \mathring{x} < Z$	yZ	yZ	
23	$y < x < Z$	yxZ		
24	$y = x < Z$	Z		

principal axes will not coincide with the system of coordinates we have chosen. Actually, only the position of the vertical axis z remains unchanged, while the orientations of the principal strain axes x and y may change with time. That is, the system of coordinates may be rotated around the z axis, reflecting a change in the directions of the external forces. The system of axes xy can, in principle, occupy an infinite number of positions in the horizontal plane. How many of these positions can actually be occupied – that is, under what conditions will new structural forms arise, reflecting new directions of the external forces acting upon the system? This question can be more conveniently considered from the standpoint of the folded forms, as the orientation of the axial planes coincides with the direction of one of the principal

[2] In speaking of the equality of the deformations along two axes, or the lack of change in the length in one of the axes, I have in mind only approximate estimates, which are almost unavoidable in tectonic analysis.

[3] The lower-case letter as before designates the axis that has been shortened, and the capital letter the elongated axis.

axes of deformation.

Experimental reproduction of the superimposed forces of longitudinal bending has produced the following results (Ghosh and Ramberg, 1968). Models of systems of linear vertical folds (regime xZ) were produced by the action of horizontal compression. Then these models were subjected to compression in directions oriented at various angles (in different experiments) to the direction of the primary compression. It turned out that when the angle α between the directions of the primary and later compression is less than 30°, no new system of folds arises, but those previously formed are further compressed. When $\alpha > 30°$, separate folds appear that are superimposed on the initial system. The greater the angle α, the more distinct is the second system of folds, which can best be discerned when $\alpha = 90°$ (that is, under the conditions of regime yZ).

If the superimposed folds arise at angles greater than 30°, one can conclude that for practical purposes only two systems of axes are realizable – the initial system xy and a diagonal system x′y′, and that the angle α between them will be within the limits of $30° < 60°$.[4] It remains to be said that the axis of the diagonal system of coordinates that has been rotated clockwise relative to the x axis is designated as the axis x′.

Thus the proposed method of detailed tectonic analysis is based on the supposition that in tectonic processes 48 regimes of deformation can be produced, of which 24 are in the system of axes xyz and 24 analogous regimes are in the system of axes x′y′z′, where z is parallel to z′ and the angle α between axes x and x′ may have any value in the interval from 30° to 60°. The regimes of the system of coordinates x′y′z′ will be designated respectively as the x′y′Z, x′Z, z′Y′Z′, etc. regimes. A general tectonic analysis can be confined to twelve main regimes, of which six belong to the system xyz and six to the system x′y′z′.

Let us cite some examples of the transition from structural data to regimes of deformation as applied to the areas considered in the first section of the present article. In the Grampian highlands – the Caledonian area of Scotland – the succession of main tectonic regimes of deformation was the following. After the formation of the Early Caledonian basins (zX-regime), thrust sheets and recumbent folds of northeast orientation (xZ-regime) appeared, then vertical folds of northwest orientation (yZ-regime), followed by vertical folds of east-west orientation. This latitudinal system of folds already belongs to a different system of principal axes of deformation x′y′z′ (diagonal relative to the primary system xyz) and indicates the regime x′Z′. In the next stage were formed vertical folds of northeast orientation (xZ-regime) and then the horizontal folds associated with left strike-slips of northeast strike (x′Y′-regime). Thus the succession of regimes of deformation in the Grampians was the following: zX – xZ – yZ – x′Z′ – xZ – x′Y′.

In the Variscides of southern Tien Shan, after the development of the geosynclinal basins (zX-regime), a system of thrust sheets and recumbent folds (xZ-regime), and then vertical folds (also xZ-regime), appeared. This was followed by the formation of basins of the orogenic type (zX-regime), then vertical folds, reverse folds and thrusts (xZ-regime) and, in the last stage, by horizontal folds and intersecting strike-slips in the regimes xY and yX.

Now let us consider in more detail the distribution of the regimes of deformation in the last stage of the folding process as it occurred in the central part of southern Tien Shan. Figure 4, 1 shows the orientation in plan of the folded structures formed in the preceding stages of folding, and Figure 4, 2 the result of the deformation in the subsequent stage. In the Turkestan-Alay sector (fig. 4, A) during this stage there was contraction along the x axis and elongation of the sector along the strike of the folded

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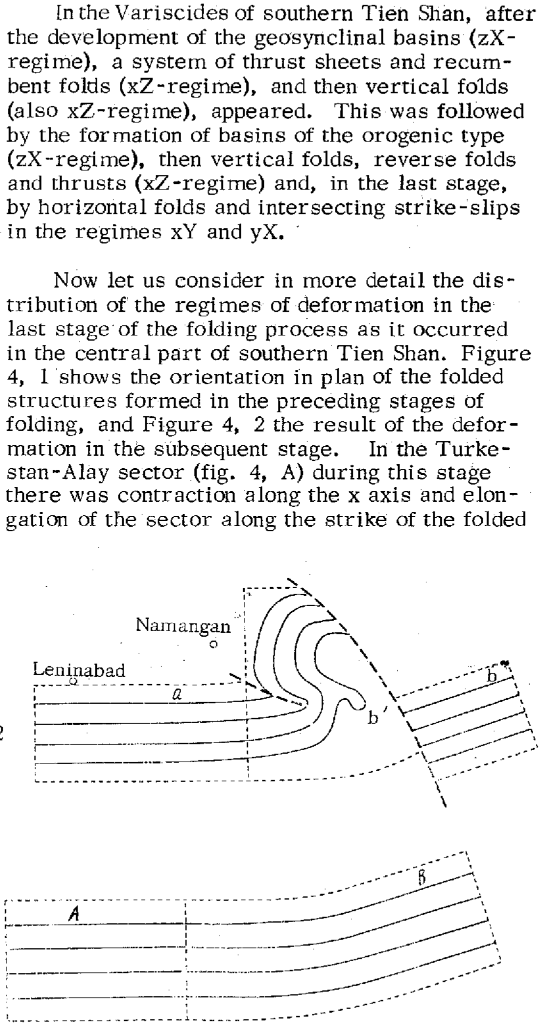

1

FIGURE 4. Central part of the Variscides of southern Tien Shan before (1) and after (2) the stage of Variscan folding.

[4]This conclusion will be exact if by the beginning of the formation of the folds in the system x′y′z′, cross folds have already been formed in the system xyz – that is, if any one of the group of x-regimes and any one of the group of y-regimes has already been realized. But if the regime of the diagonal system x′y′z′ arises earlier than the regime of the y group, the symmetry may later be broken: structural forms may appear whose smallest axis of deformation is oriented at a small angle to the theoretical direction of the y, x′ or y′ axis. In view of the approximate nature of all the magnitudes in a tectonic analysis, one can disregard small angular deviations and, without complicating the system, consider the structures mentioned as belonging respectively to the group of y, x′ or y′ regimes.

structures along the y axis. An indication of the elongation along the y axis are the small strike-slips that cut obliquely across the folded structures. At the same time, apparently, there was further compression of the vertical folds that had been formed in the previous stage, so that on the whole what was realized was the regime xZY.

The Fergana sector (fig. 4, B) underwent the greatest change. It was torn into two parts by the Talaso-Fergana strike-slip fault, the displacements along which also are a part of the xZY system. The western part of this sector (fig. 4, b′) underwent sharp contraction along the y axis, which was compensated mainly by elongation along the x axis with the formation, within this part of the sector, of a large horizontal flexure and horizontal folds. This rearrangement of the structure was accompanied by compression of the vertical folds deformed in the horizontal plane — that is, on the whole, the regime yXZ was realized. The structural data on the eastern part of the Fergana sector (fig. 4, b) indicate that in this area a regime similar to that of the Turkestan-Alay sector was realized (xZY).

Thus the Turkestan-Alay and eastern part of the Fergana sectors were characterized by the following series of main tectonic regimes of deformation: zX – xZ –xZ –zX – xZ – xY, and the western part of the Fergana sector (fig. 4, b′) by zX – xZ –xZ – zX – xZ – yX. Each series consists of six regimes, and the series differ only in their last members. Now let us look at the regimes that appeared in the series more than once. These are the regimes I and IV (zX-regimes) and II, III and V (xZ-regimes). The structural data permit the conclusion that the deformation of regime I was much greater than in IV. That is, on the ternary diagram regimes I and IV are located in the same sector, but the point of regime IV lies closer to the center of the diagram. Among the second group of regimes with the same designations the greatest deformations were those of regime II and then V, whereas the effect of the deformations in regime III was very slight (fig. 5). We can similarly obtain the following record of successive tectonic regimes of deformation: zX –xZ –xZ –xZ – xY′ for the New Zealand Alps, and zX – xZ –xZ –xY for the central Pamir region.

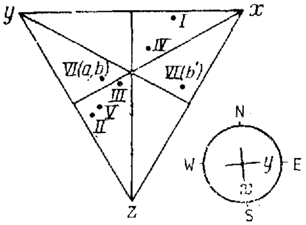

FIGURE 5. Main tectonic regimes of deformation for the central part of the Variscides of southern Tien Shan

In such a record the history of the deformation of a geologic body emerges very prominently: the principal effects are clearly separated from the secondary and random results. The critical moments of the development can be distinctly seen: the transition from horizontal extension (zX-regime) to horizontal compression, from deformation in the vertical plane (xZ, zX-regimes) to deformation in the horizontal plane (xY-regime), the character of the superimposition of one deformation on another, and so forth.

CONCLUSION

Analysis of the stages of folding (Section I) reveals the evolution of the folding process within the tectonic cycle. This analysis enables one to divide a folded region into zones corresponding to the history of the folding (Burtman, 1970). On the other hand, comparison of the evolution of the folding processes in regions with folding of different ages shows typical successions — sets of folding processes, one of which was considered in this article. The deformation of geologic bodies under the very same dynamic conditions may follow quite different paths, depending on the distinctive local features of the structure. As a result, a structural pattern often emerges that is unique in each separate area, and the comparison of such patterns is extremely difficult. An advantage of the analysis of regimes of deformation (Section II), apart from its universality, is that it permits one to disregard the particular structural manifestations of the deformations — that is, to compare the main result of the deformation, regardless of the way in which this result was achieved. Another advantage of this form of analysis is that the systems of three-dimensional coordinates within which the analysis is made are not determined relative to the cardinal points of the compass, but are tied directly to the folded zone. The result thus obtained eliminates errors arising from the curved shape of the folded belt, subsequent rotation of the crustal blocks and so forth. All this increases the usefulness of the method in the comparative study of folded complexes.

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