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Morphology and origin of folding in the South Tien Shan

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Abstract. The qualitative and quantitative analysis of the holomorphic folding morphology in the central segment of the South Tien Shan revealed its heterogeneity in the Paleozoic rock sequences. Against the background of the gradual folding simplification from the axial parts of the mountain system to its periphery, the relatively intense dislocations alternate with less tense structural fields. The former are restricted to the anticlinoria and large anticlines, the latter, to the synclinoria and large synclines. The study of the fold formation history proved the fact that the recent orogenic structures had been inherited from the anticlinoria and synclinoria of Hercynian time. The disharmonic and highly variable folding of the South Tien Shan seems to have originated as a result of the combined effects of three factors: (1) the deformation of the allochthone rocks during the gravitational movement of the tectonic nappes; (2) the external subhorizontal reduction of the crystalline basement and the overlying volcanic and sedimentary rock sequences, and (3) advective movements in the rocks of the sedimentary cover.

Introduction

The Hercynian fold system of the South Tien Shan is well known for the wide development of different morphological types of folding both in the Hercynian and Alpine rock complexes (see a photograph in Figure 1). The South Tien Shan is a standard area, the long study of which resulted in the formulation of a main theory for the Alpine orogenesis of old fold mountains [*Shultz,* 1937] (Figure 2), for deep crustal faults (papers by A. V. Peive and A. Suvorov), for the facies and formations of sedimentary and igneous rocks [*The problems...,* 1973], and the views were advanced for the geology and mechanics of shears and nappes] [*Burtman,* 1973, 1976; *Porshnyakov,* 1973]. The territory is divided into structural zones, where the main fold structures were mapped: anticlinoria and synclinoria (Figure 3) [*Akhmedzhanov et al.,* 1979; *Biske,* 1996; *Burtman,* 1973, 1976; *Dovzhikov,* 1977; *Klishevich,* 1986; *Kukhtikov,* 1968; *Leonov,* 1985, 1990; *Masumov et al.,* 1978; *Porshnyakov,* 1973; *The problems...,* 1973; *Sinitsyn,* 1960; *The tectonics...,* 1989; *Zamaletdinov et al.,* 1968]. However, the systematic studies of the Paleozoic folding were initiated there as late as the seventies of the 20th century [*Rogozhin,* 1977, 1986, 1993; *Volochkovich et al.,* 1979]. Yet, the problems of the structural relations between the fold zones, nappes, and deep faults remained unsolved. At the end of the 1980s, views were advanced that the fold deformations that produced the structural pattern of this zone had operated during the Alpine period of the geological history [*Yablonskaya,* 1989], rather than during the Hercynian time, as believed earlier [*Chedia,* 1972; *Dovzhikov,* 1977]. No consensus has been achieved on the dating of this fold structure. At the same time this problem remains to be urgent, because many of the modern reconstructions are based on different views on the structure of the South Tien Shan fold system. In particular, the highly debatable item is the dominant role of the horizontal compression exerted on the Tien Shan from the Hindustan protrusion of the Gondwanaland and from the lithospheric blocks of the Pamirs and Afgan-Tajik mountain massifs (Figure 2) during the formation of the recent, and possibly, of the Paleozoic fold-and-nappe structure of this mobile system [*Abdulaev et al.,* 2002; *Yakovlev and Yunga,* 2001]. In my study I investigated, with a varying degree of detail, the structural geology of several areas in the South Tien Shan region [*Rogozhin,* 1977, 1986, 1993]. The results of these studies allowed me to return to some unsolved prob-

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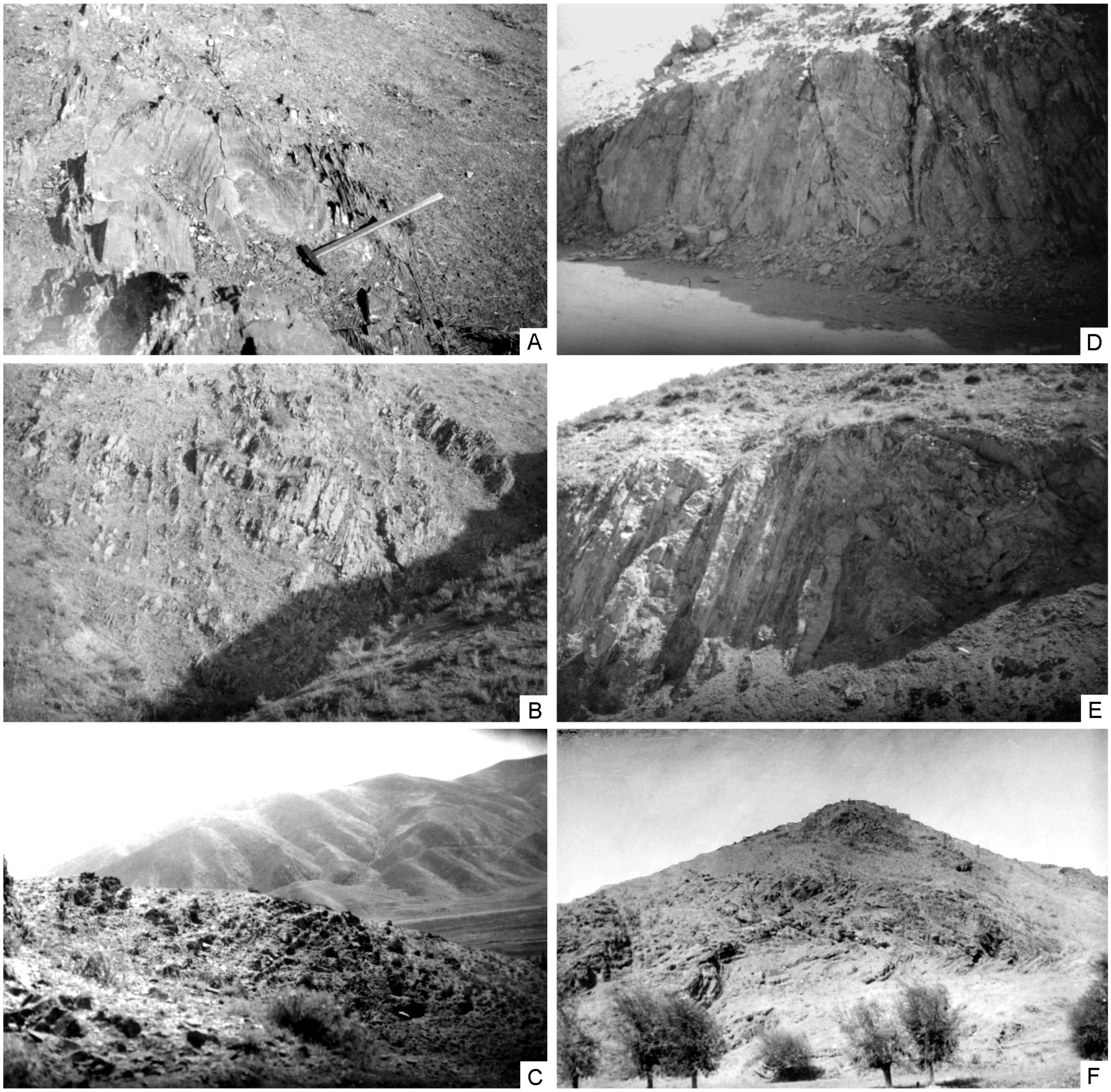
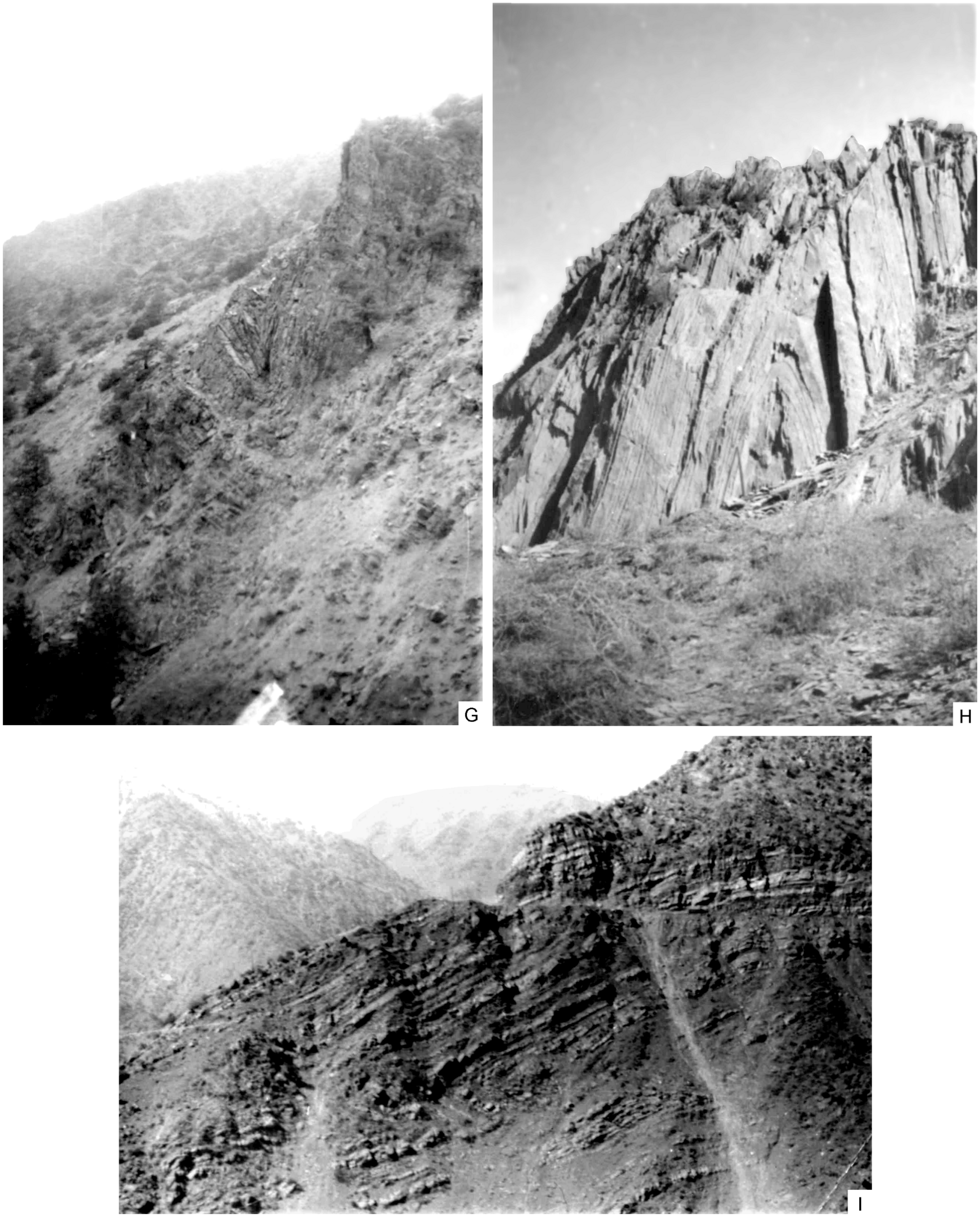


Figure 1. Photographs of fold dislocations in the territory of the Turkestan Range, Southern Tien Shan. A – an anticlinal fold in the sequence of Lower Silurian cleavaged argillite and siltstone (Uab-Rawat River valley, Shakhristan Pass area); B – a synclinal fold in the sequence of cleavaged Lower Silurian shale and siltstone (Uab-Rawat River valley; C – a vertical anticlinal fold in the Lower Silurian cleavaged shale and siltstone sequence (Argly R. Valley); D – inclined anticline in the sequence of Lower Silurian shale and siltstone (Shakhristan Pass area); E – inclined anticline in the Lower Silurian sandstone and siltstone (Argly R. Valley); F – recumbent folds in the sequence of Lower Paleozoic shale and siltstone (Zaaminsu R. Valley); G – a carinate syncline in Lower Silurian cleavaged shale and siltstone (Argly R. Valley); H – recumbent folds in the sequence of Lower Paleozoic shale and siltstone (Zaaminsu R. Valley); I – recumbent folds in the Lower Silurian sandstones and siltstones (south of the Shakhristan Pass).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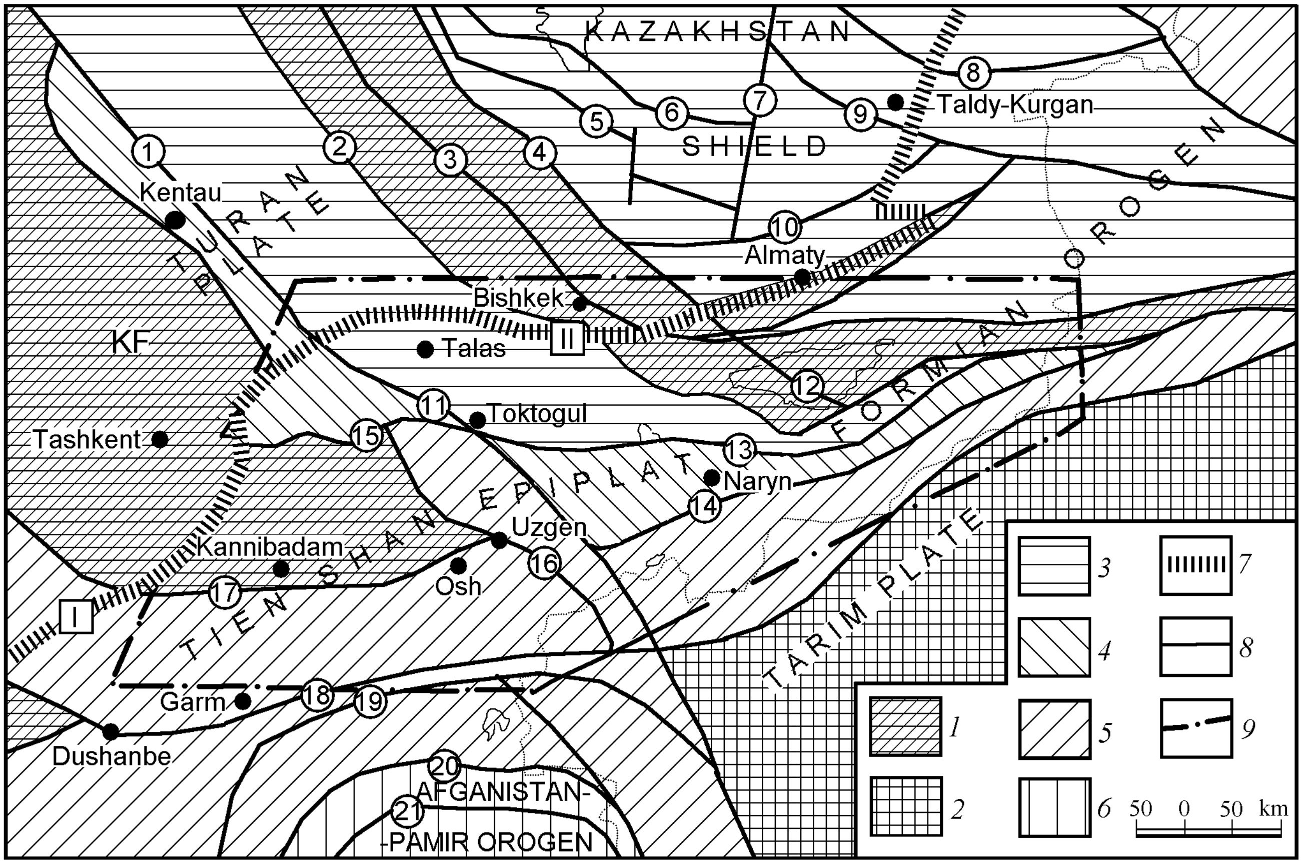


Figure 2. Schematic map of the Tien Shan epiplatform orogenic belt [modified after *Dzhamalov et al.,* 1986]: (1) intermountain basins and foredeeps superimposed over the Kazakhstan and Kyzyl-Kum–Fergana median masses; (2) a trough superimposed over the Tarim Plate median mass and Alpine orogenic uplifts formed in the epi-Caledonian basement (Northern Tien Shan) (3), in the Early epi-Hercynean basement (Middle Tien Shan) (4), and in the Late epi-Hercynian basement (South Tien Shan) (5); (6) Afganistan-Pamir Alpine orogenic belt; (7) NW boundary of the Tien Shan orogenic belt; (8) the largest recent faults (their numbers denote the faults that are insignificant for this paper, except for the faults surrounding the studied regions of the South Tien Shan: no.11: Talas-Fergana Fault, no.16: the fault of the Fergana Range; no. 17: South Fergana Fault, and no. 18: the South Gissar Fault); (9) the outline that is of no importance for this paper.

lems of the South Tien Shan, formulated in the 1970s and 1980s. In my interpretation of the field data I used the methods of the qualitative and quantitative descriptions of folds and fold-related faults. This work revealed the great morphologic heterogeneity of the folds in the area of this mountain system. The disharmonic attitudes of size-varying folds in the sedimentary and volcanic rock sequences, as well as the structural relationships among the folds, faults, and nappes, indicated the complex multifactor character of the folding process. The comparison of the folding intensity in the Paleozoic and Meso-Cenozoic rocks allowed me to trace the evolution of the holomorphic folding pattern formation in time.

Methods of Data Collection and Interpretation

In order to collect information on the real forms of folds and faults, special-purpose field surveys were carried out in the seventies and eighties of the last century across the strike of the fold system. The documented materials included the description of the structural features of varying-size folds, plication, cleavage, boudinage and the overlapping of the folds of two or more generations in the sediments and, especially, in the metamorphic rocks. Where large folds could not be traced or were present in fragments, the monoclinal rock

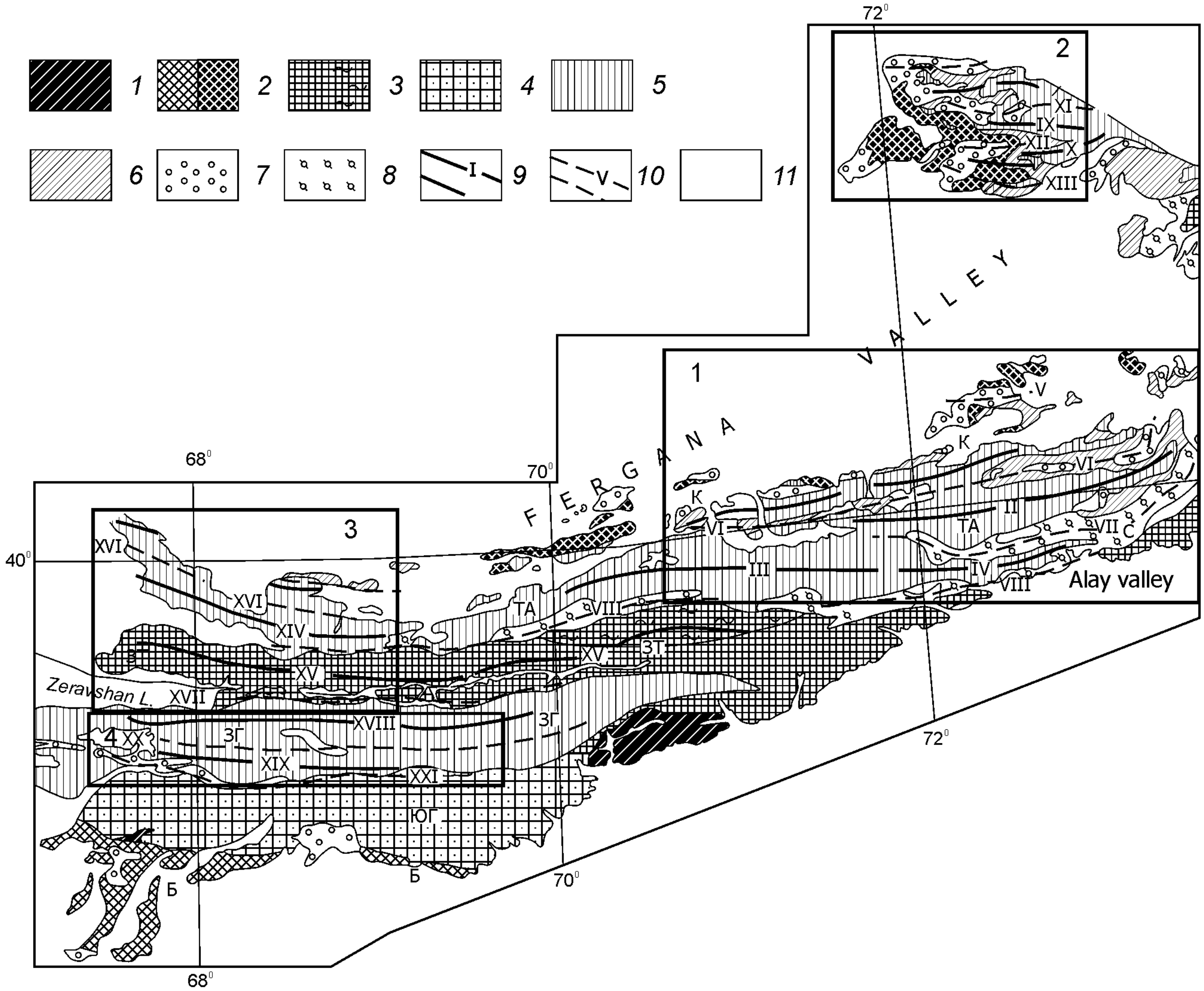


Figure 3. The map of the structural and formation zones of the South Tien Shan: (1–8) Hercynian formations: (1) old basement rocks (Garm Massif of metamorphic rocks), (2) sedimentary rocks of the median and marginal massifs: (a) autochthonous, (b) allochthonous; (3) rocks from Early Hercynian central uplifts: (a) with the development of early metamorphism, (b) with the development of high-grade metamorphism (Turkestan Complex); (4) same with the wide development of batholith-type granitoids (South Gissar Zone); (5) rocks in Early Hercynian foredeeps; (6) rocks in volcanic "island-arc" troughs; (7, 8) rocks that had accumulated during the epi-Hercynean evolution phase: (7) in marginal foredeeps, and (8) in internal fault-related basins; (9) anticlinoria; (10) synclinorium; (11) alpine formations.
The framed areas are the following study areas: the Alai Range (1), the Baubashata Mountain Assembly (2), the Turkestan Range (3), and the Zeravshan-Gissar Range (4). The largest fold structural features are the Kauzan (I), Kichikalai (II), Khodzhaachkan (III), and Kulgedzhili (IV) anticlinoria, and the Aravan (V), Okhna-Taldyk (VI), Surmetash (VII), and Daraut-Turkestan (Kurganak) (VIII) synclinoria.
The Baubashata area includes the Kainda (IX) and Seresui (X) anticlinoria (megaanticlines) and the Isfandzhailoo (XI), Kerei (XII), and Sarybel-Mailisu (XIII) megasynclines.
The Turkestan area includes the Malguzar (XIV) and Zeravshan-Turkestan anticlinoria, and the Fan-Margib (XX) and Zidda-Karakul (XXI) synclinoria.

packages were examined. Particular attention was given to the exact location of the bottoms and tops of the layers. All large and small breaks and faults were mapped with a special attention given to the zones of regional faults. All data collected for the faults and folds were plotted in geological sections of 1:10 000 or 1:25 000 scales. These sections were plotted across the strikes of the fold zones at equal distances from one another. As a result, the study areas were covered, more or less equally, by structural observations [*Rogozhin,* 1977, 1986, 1993; *Volochkovich et al.,* 1979].

The analysis of the cross-sections does not give a complete idea of the region's structure. One can only locate and trace, along the strike, the zones of different types of disturbances. Whereas the relations among the dislocations of different orders and the zonal pattern of folding could be understood only in the course of areal studies. The work of this kind was done in the most complicated areas and in the areas where the study profiles were comparatively rare [*Rogozhin,* 1977].

The main purpose of this study is the detailed classification of folding into morphological types. It had been believed conventionally that in terms of its morphology the Paleozoic folding pattern in the South Tien Shan region was uniform and linear, that is, holomorphic [*The problems...,* 1973; *Sinitsyn,* 1960; *The tectonics...,* 1989], whereas the results of field observations suggest the substantial heterogeneity of the folding pattern [*Leonov,* 1985, 1990; *Rogozhin,* 1977, 1986, 1993].

To be more objective in the location and tracing of the longitudinal and transverse heterogeneities of any fold structure, we used two qualitative methods of estimating the complexity of the folds. One of them was the formalized method of the quantitative estimation of morphological folding complexity (MFC) [*Rogozhin,* 1986]. This method had been devised and offered for analyzing series of detailed geological sections crossing fold areas across their strikes. Such estimations are performed in previously located cross-section segments, commensurable in size, or structural domains, showing a network of morphological indications, the sum total of which is necessary and sufficient for ranking the mapped folding types with the known morphological varieties. The folding morphology is comparatively uniform in each domain. The boundaries between the domains are drawn in the places of notable changes in the folding morphology or along the zones of large faults.

We used the following morphologic indications of fold deformations: (1) an angle between the fold limbs, (2) a degree of similitude between anticlinal and synclinal forms, (3) the presence of cross-cutting cleavage, (4) a ratio between the fold curve and limb widths, (5) the dip angle of fold axial surfaces, (6) a ratio between the numbers of larger and smaller folds, and (7) the position of a fine folding plane. The holomorphic (MFC = 1.0) and intermediate (MFC = 0.1) folding types [*Belousov,* 1975, 1985], characteristic of the central and peripheral zones of the fold systems are usually found, as a result of using this analytical approach, to be the extreme members of the gradual series of smaller morphological forms. Each of the indications was estimated to be equal to 0.1 or 0.2 for highly significant indications. As a result, each structural domain in each cross-section has a series of estimates for each indication and a sum total can be estimated.

In my study I usually analyzed the forms of small folds, which can be observed in the field. These are folds of the third and fourth orders of magnitude. Four classes of folds were located confidently in the South Tien Shan region. The first type includes the folds whose widths and heights measured a few kilometers and lengths, dozens of kilometers. In terms of the third order of magnitude, these values are hundreds of meters and kilometers, respectively. Fourth-order folds (Figure 1) were observed in outcrops, because their sizes measure meters and dozens of meters (and may be as large as a hundred of meters).

The MFC estimates for the domains located in each geological section allow one to trace and estimate quantitatively the heterogeneity of the forms of small folds over an area by way of interpolating the values obtained for all geologic sections available.

The resulting MFC values can be compared with the results of the earlier used methods of the qualitative estimation of folding intensity, which are more usual for many geologists [*Sholpo,* 1978]. The highest MFC values (0.75–1.0) are known for the zones of most compressed isoclinal folds, the intermediate MFC values (0.6–0.7), for the zones of folds with less intense curves, comparatively low MFC values (0.3–0.55), for the zones of arcuate or round forms, and the lowest MFC values (0.1–0.25), for carinate and box-shaped folds. Another quantitative parameter used to estimate the compression degree of the folded rocks was the so-called coefficient of the excessive length of the layers (λ), which is derived by calculating the ratio of the curvimeter-measured length of the layers of folded rocks measured using a curvature meter in the cross section to the horizontal length of the measured rock segment [*Vikhert,* 1972]. This characteristics reflects the degree of the horizontal reduction of the sedimentary rock basis in the course of folding, that is, the excessive length of the layers. This estimate allows one to compare the cumulative fold deformation, measured in the Paleozoic rocks, and the recent deformation, measured in the rock sequences of Paleozoic age, with the recent deformation estimated only in the Mesozoic and Cenozoic deposits.

The morphology of the co-folding faults was studied using the conventional methods employed in structural geology [*Belousov,* 1975, 1985]. The inclined faults recorded in each section were classified in terms of their morphology as normal faults, reverse faults, or thrust faults. Using the amounts of the relative displacements of the rock layers of the same age, the absolute amounts of the vertical and horizontal displacements in the fault sides were found and the faults were classified as normal or upthrust faults, and the relative amounts of compression and extension were calculated in per cent relative to the total length of the section.

Displacements along the faults were estimated in large fold structures, such as anticlinoria and synclinoria, this allowing one to characterize the latter not only in terms of the heterogeneity of the plicated rocks, but also in terms of the contribution of the faults into the general deformation pattern.

Morphological Heterogeneity of the Fault and Fold Structure

The Turkestan and Alai structural features have been studied in most detail [*Rogozhin,* 1977, 1993]. The fold zones are characterized there by a complex linear folding style and by the development of huge anticlinoria and synclinoria against the background of widely developed pre-folding nappes.

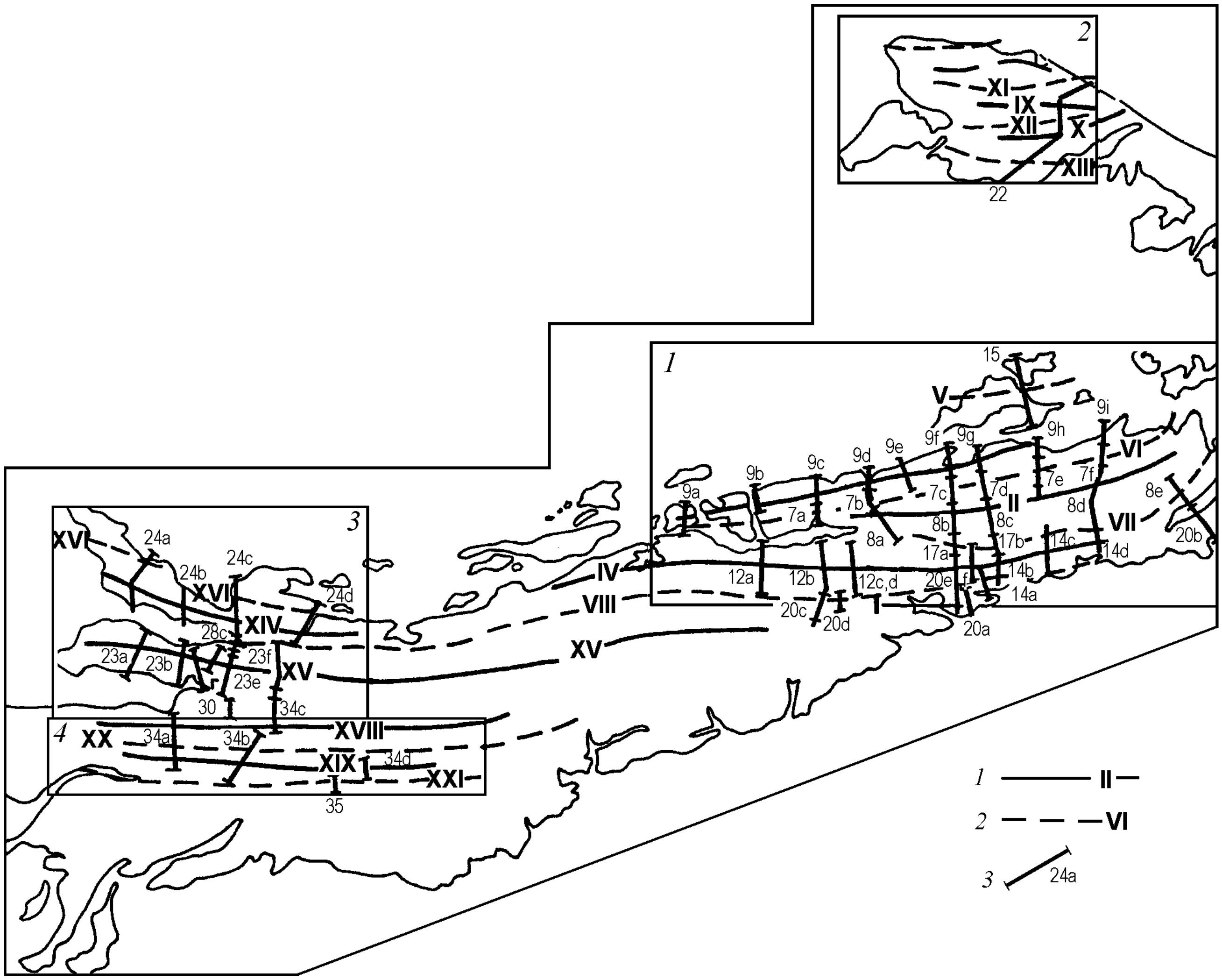


Figure 4. Location map of the geological cross-sections in the territory of the South Tien Shan (based in Figure 3): (1) axes of anticlinoria, (2) axes of synclinoria; (3) lines of geological cross-sections (their numbers correspond to the numbers of the figures showing these cross-sections, see below).

The Zeravshan-Gissar zone was studied along individual cross-section lines. Yet, the detailed structural studies done there by *Leonov* [1985, 1990] allowed us to have an idea of its fold-and-nappe structure, with numerous imbricate nappes which do not fit one system of nappes [*Leonov,* 1990].

Discarded from our study were the South Gissar and Baisun tectonic zones, because the former is almost wholly occupied by the granites of the Gissar Pluton, and the latter is poorly exposed, this precluding the systematic study of the folding morphology. Finally, the Baubashata mountain area, located northeast of the Fergana Basin, is characterized by only one cross-section, this demanding the discussion of this cross section only on the condition of comparing it with the data from the better known zones.

Our study of the above mentioned areas in the South Tien Shan region allowed us to get a general idea of its structure in the central segment of the fold zone (Figures 3, 4), the main structural elements of which are tectonic nappes, large anticlinoria and synclinoria, as well as numerous smaller folds, and a system of regional and local faults.

The formation of the Hercynian tectonic nappes preceded the main folding epoch. The packages of the nappes (sheets) experienced folding, like the stratigraphic rock sequences, and participated in the formation of synclinoria and, to a lesser extent, of anticlinoria [*Burtman,* 1973, 1976; *Klishevich,* 1986; *Volochkovich et al.,* 1979]. Associated with the movements of the tectonic nappes, was the formation of early drag folds, encountered in the allochthonous sheets. These folds are best developed and are most numerous in the frontal parts of the latter and are scarce in their backs, where the beds experience subhorizontal stretching. The inner fold structure of the allochthon is shown in Figure 5 using the example of the Tegermach outlier.

The tectonic zones that had been mapped earlier in the area of the South Tien Shan show substantial differences in the composition and thickness of the Middle Paleozoic

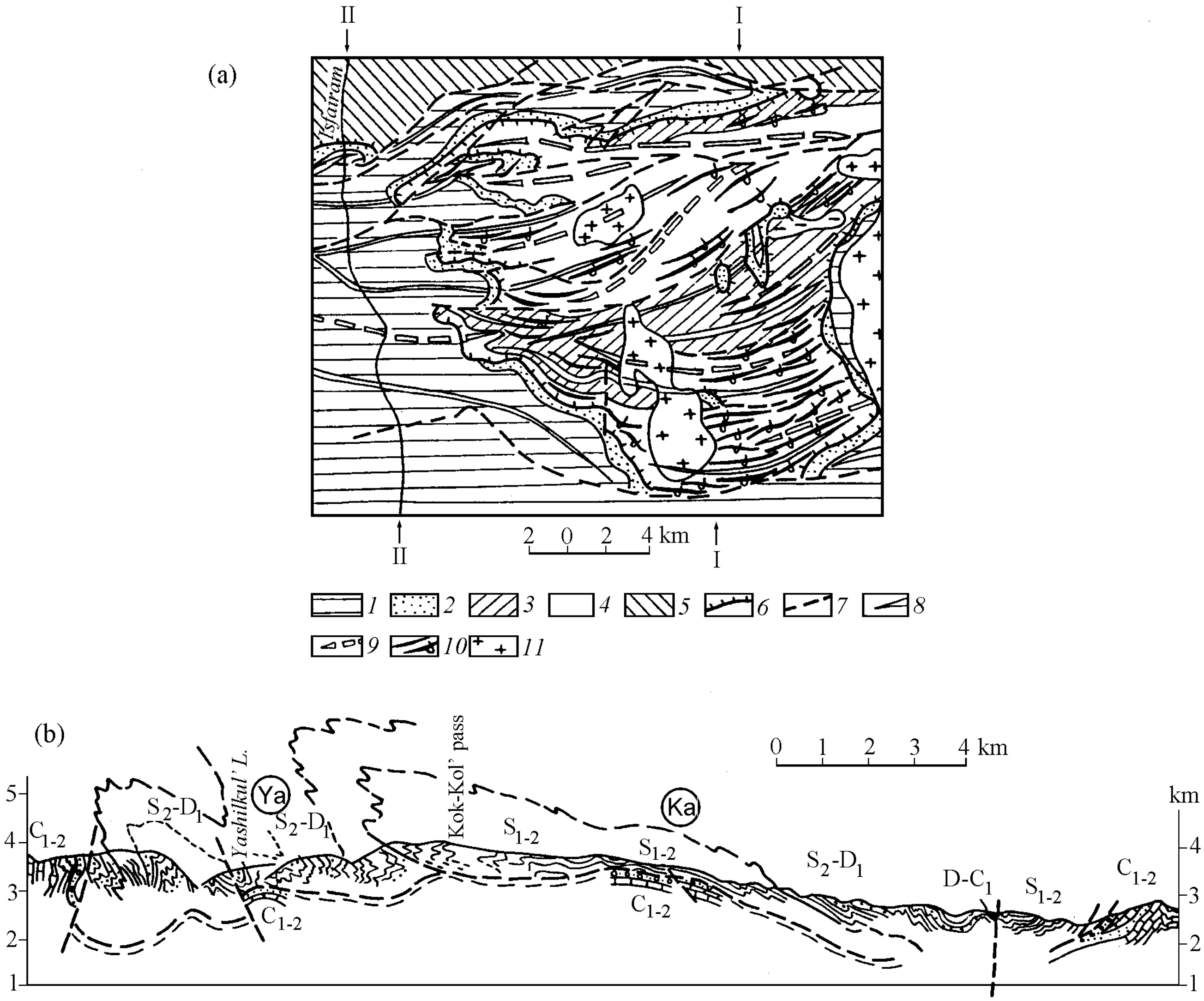


Figure 5. The schematic geological map (a) and section (b) of the Tegermach tectonic nappe (section I–I along the valleys of the Abshirsai, Kek-Kel, and Tegermach rivers. The legend for the map: (1–2) the rocks of the limestone-dolomite subzone of the autochthone: (1) a limestone and limestone-dolomite suite, (2) marine flyschoid molasse of the Middle Carboniferous Moscovian Stage; (3–4) allochthonous complex: (3) Lower Silurian sandy-shaly deposits, (4) Upper Silurian sandy-shaly and Lower Devonian carbonate (limestone) deposits; (5) Silurian sandstones and shales beyond the limits of the overthrust; (6) overthrust borders of the Tegermach tectonic nappe; (7) faults; (8–9) large folds: (8) anticlines, (9) synclines; (10) small anticlines; (11) granitoids of the Kichikalai Batholith and its satellites. See Figure 6 for the legend for the section.

rocks and, hence, in the tectonic environment in which these rocks had deposited . Widely developed and bordering one another are the zones of "shelf" (carbonate-terrigenous) sedimentation, "island-arc" (volcanic-type) evolution, and "paleooceanic" (condensed-type siliceous rocks and ophiolites) of the Paleozoic history. The specific feature, common for the Paleozoic rocks in all zones, is the fact that the clay-shale rock sequences of Silurian and, partly, of Early Paleozoic age, composing the bottoms of all types of rock sequences, are stratigraphically higher replaced everywhere by more compact rocks, such as the Middle Paleozoic volcanic, siliceous, or carbonate rocks. Therefore, all types of rock sequences show a density inversion.

The tectonic nappes are composed of Middle Paleozoic volcanic and siliceous ophiolitic rocks. They are most abundant in the northern zones of the South Tien Shan region, namely, in the Karachatyr, Turkestan-Alai, and Baubashata zones at the boundary with the Fergana-Kyzylkum Median Massif and are almost totally absent in the Zeravshan-Turkestan and Zeravshan-Gissar axial zones of the system. It is remarkable that overthrusts are equally well developed in the areas of the latest intensive folding (Alai Range,

Table 1. Average values of the coefficient of the excessive length (λ) of the layers for the South Tien Shan anticlinoria

Sample	The name of anticlinorium	An average value of λ	The number of evaluated sections
1	Kauzan	1.28	20
2	Kichikalai	1.52	4
3	Khodzhaachkan and Malguzar	1.77	15
4	Zeravshan-Turkestan	1.89	7
5	Zeravshan Range	1.75	6
6	Gissar	1.31	3

Figures 5 and 6), and in the cases of its relatively mild manifestations (Baubashata, Figures 7 and 8), this suggesting the independent developments of the folds and overthrusts. At the same time there is an obvious relationship between the regional faults and large fold zones: the faults divide many anticlinoria and synclinoria, some synclinoria having been formed along large fault zones.

Each of the largest fold structures shows an abrupt repeated replacement of some rock series by some other ones, the boundaries between such extensive and narrow blocks, being composed of different rocks (for instance, island-arc and shelf ones) showing no indications of transitional rocks. Such blocks are usually separated by faults. The individual blocks are usually 5–10 km, or sometimes 15 km wide, with their lengths ranging between 100 and 150 km. No correlation can be established between any definite structural and formation zones, except that the sequences of the "island-arc" and "paleooceanic" (siliceous ophiolite) zones are usually restricted to the cores of the synclinoria (Figure 6), as are the Late Paleozoic molasses, whereas the rock sequences with the shelf type (terrigenous-carbonate) rock sequence usually occupy the cores of the anticlinoria or the limbs of the anticlinoria and synclinoria (Figure 9).

Fine folds of varying morphology are distributed extremely nonuniformly in the large folds and in the fold system as a whole (Figures 1 and 2). We analyzed this morphological heterogeneity separately for the anticlinoria (Figures 9, 10–18) and the synclinoria (Figures 6, 17, 18, 19–30) to be able to compare the fold dislocations in lithologically similar rocks.

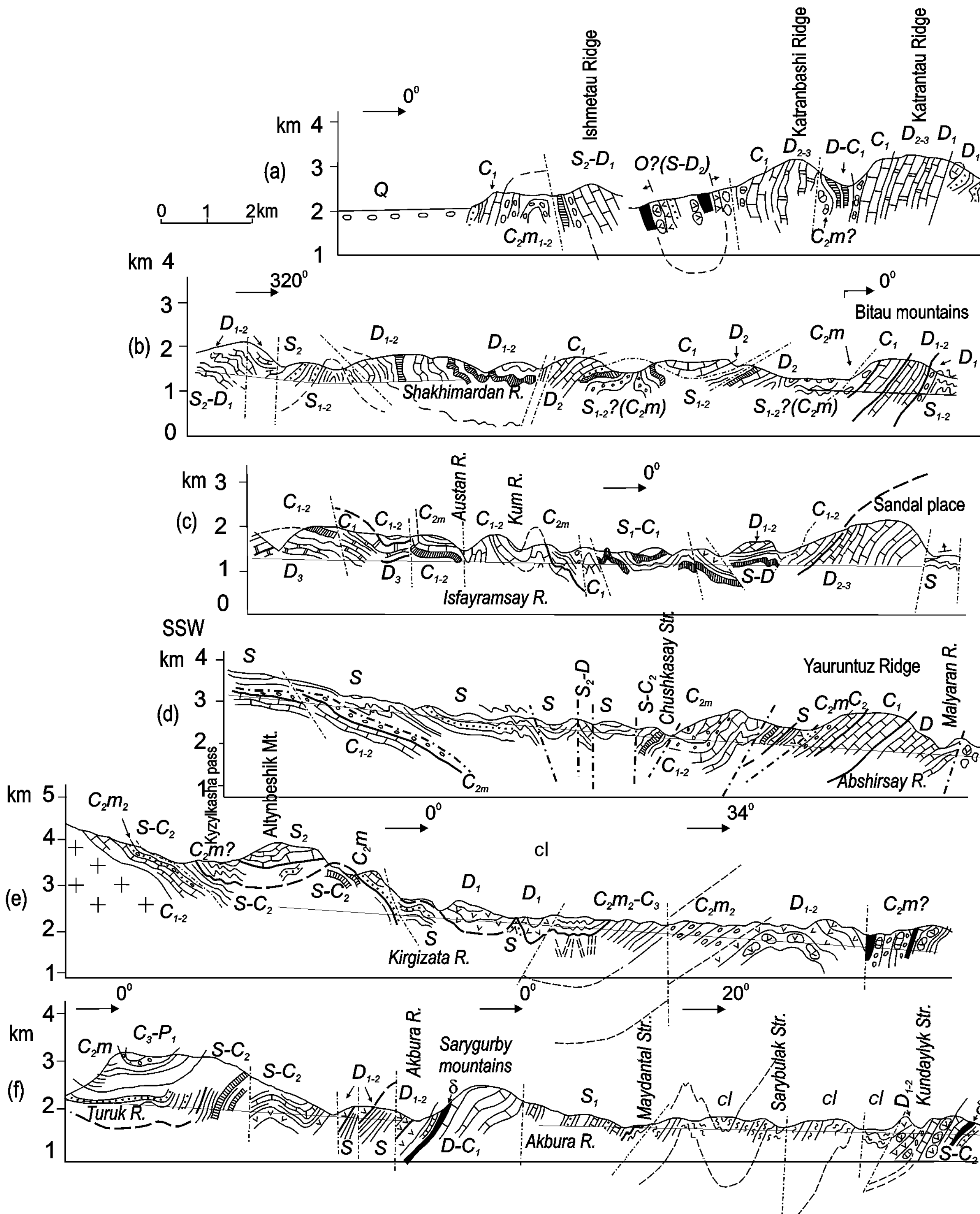
In the South Tien Shan area we studied the structure of seven anticlinoria having sublatitudinal strikes and extending for hundreds of kilometers with the widths ranging between 15 and 30 km. Extending from the north to the south, these are the Kauzan, Kichikalai, and Khodzhaachkan anticlinoria in the Alai segment of the fold system, and the Malguzar, Zeravshan-Turkestan, Zeravshan Range, and Gissar in the Turkestan-Gissar segment (Figures 3, 4, 9, 10, 13, 15–17). The anticlinoria are composed mainly of autochthonous carbonate or terrigenous deposits of Middle Paleozoic age and are often arranged en-echelon. For instance, the Kichikalai continues southwest as the Khodzhaachkan, and the latter extends as the Zeravshan-Turkestan (Figures 3 and 4).

The folding morphology varies across the strike of the South Tien Shan fold system. The large (first-order) folds composing the cores and limbs of the anticlinoria in the axial part of the fold system (Zeravshan-Turkestan, Khodzhaachkan, and Zeravshan Ranges) are complicated by numerous linear, tightly compressed, often isoclinal smaller folds (of 2nd, 3rd, and 4th orders), which form, along with local faults, upward open fans (Figures 13, 16, and 18). The cross-section structure of these anticlinoria can be termed divergent. There are also gently dipping, bowl-shaped brachyform folds and imbricate fold structures.

The large and smaller folds complicating the former in the anticlinoria from the peripheral parts of the fold system (Kauzan, Kichikalai, Kulgedzhilin, Malgauzar, and Gissar) usually have a round, box-shaped, or comb-shaped form; less common are acute-hinged dislocations (Figures 9, 10, 15, 17, and 18). The monovergent orientation is characteristic of the structural elements. The axial surfaces of the folds are inclined in the direction of the margins of the fold system, where vergence may be absent at all.

The computation of the coefficient of the excessive length of the layers [*Vikhert,* 1972] (Table 1) for each of the anticlinoria described showed the maximum values in the axial Zeravshan-Turkestan (1.89), which decline slowly in the marginal anticlinoria (1.28–1.31). As has been shown above, folding intensity decreases in the same direction. The typical holomorphic folding, characteristic of the axial parts of the system, is replaced by simpler forms in the periphery. The MFC estimates show higher values (0.6–1.0) over the large areas of the anticlinoria in the central part of the fold system. Its marginal parts are dominated by moderate and low values (0.1–0.55), although there are some narrow strips where the MFC values are fairly high (Figure 31).

Folding becomes simpler and more heterogeneous along the strikes of the large folds away from the central parts of the anticlinoria toward their periclinal parts. The typical examples are the large and small complicating folds at the periclines of the Kichikalai and Khodzhaachkan anticlinoria, which acquire a box-shaped or a crestlike form (Figures 9 and 13). In the case of the Zeravshan-Turkestan (Figures 16 and 32) it was found that the one field of complex folding (Figure 33) with high MFC values (MFC = 0.85–1.0), typical of its eastern part, had been broken into individual comparatively narrow bands, separated and, in the south surrounded by linear zones with intermediate MFC values (0.55 to 0.8). These linear bands with fine folding of variable complexity generally coincided with larger anticlines and synclines, respectively. Worthy of note is the en-echelon pattern of their localization and the diminishing values of the excessive lengths of the layers (λ) (Figure 34).



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Isfayramsay R.
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Yauruntuz Ridge
Chushkasay Str.
Malyaran R.
Abshirsay R.
Kyzylkasha pass
Altynbeshik Mt.
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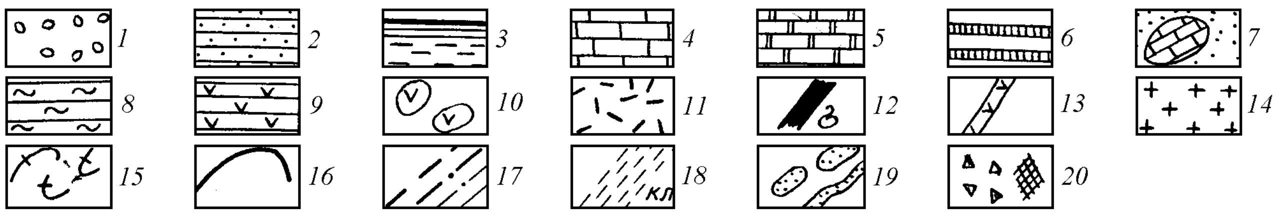

Figure 6. (*On the left side.*) Geological sections across the Okhna-Taldyk synclinorium: (a) north of Khaidarkan Village (Sartaly R. Valley); (b) Shakhimardan R. Valley; (c) Isfairamsai R. Valley; (d) Abshirsai R. Valley; (e) Kirgizata R. Valley; (f) along the Akbura R. and Turuk R. Valleys.
Legend for the geological sections across the South Tien Shan: (1) conglomerate and gravelite; (2) sandstone and siltstone; (3) argillite and shale; (4) limestone; (5) dolomite; (6) siliceous rocks; (7) olistostrome and olistolith; (8) greenschist metamorphics; (9) basic and intermediate volcanics (basalt, andesite); (10) pillow lava; (11) acid volcanics (rhyolite, dacite, and their tuffs); (12) ultrabasic rocks, serpentinite; (13) diabase dikes; (14) granitoids; (15) granite-gneiss and gneiss; (16) stratigraphic boundaries; (17) faults; (18) cleavage; (19) lenses and boudinage; (20) fault-bordering tectonic breccias.

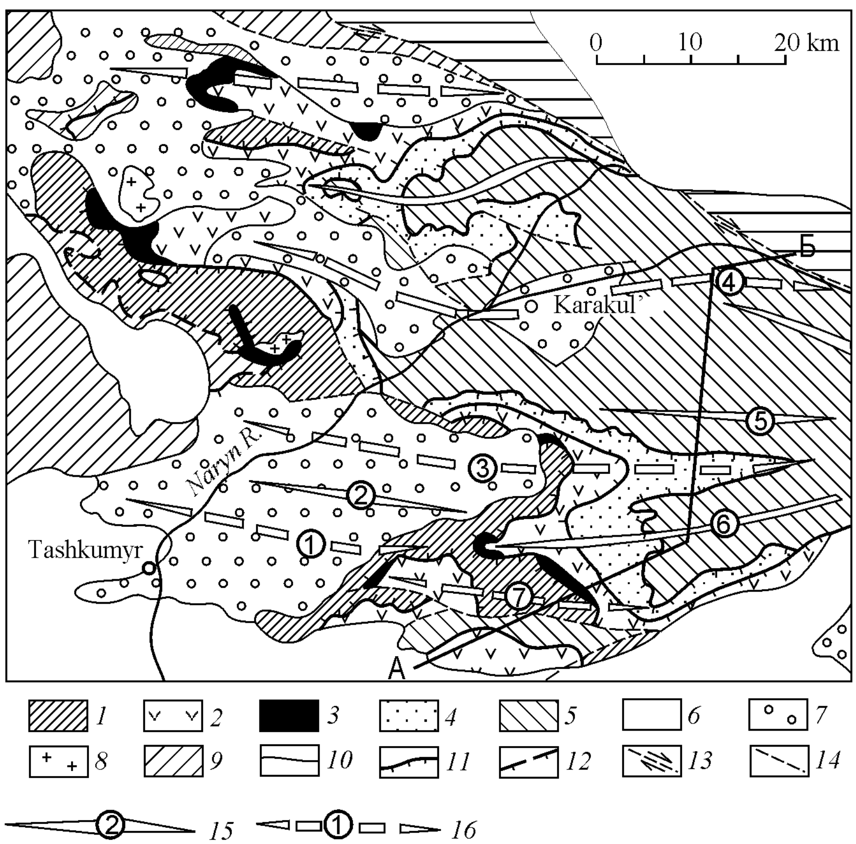

Figure 7. Schematic structural map of the Baubashata Mountains: (1–4) Lower and Middle Paleozoic rocks: (1) greenschist complex of metamorphic island-arc rocks, (2) unmetamorphozed island-arc volcanics, (3) serpentinized ultrabasic rocks, (4) condensed terrigenous silicic (paleo-oceanic-type) rocks; (5) shelf-type (autochthonous) limestones and dolomites; (6) Mesozoic and Cenozoic sediments; (7) Late Paleozoic molasse; (8) granitoids; (9) Middle Tien Shan structure-formation zones (Chatkal-Kurama Fold System); (10) North Tien Shan structure-formation zones; (11) nappes; (12) overthrusts; (13) strike-slip faults, (14) other faults; (15–16) large folds: (15) anticlines (and anticlinoria), and (16) synclines (and synclinoria). The names of the largest fold-type structural features: (1) Sarybel Megasyncline, (2) Ryazan megaanticline, (3) Kerey Megasyncline, (4) Isfandzhailoos Megasyncline, (5) Kainda Megaanticline, (6) Seresui megaanticline, (7) Mailisui Megasyncline. A–B is the line of the section shown in Figure 8.

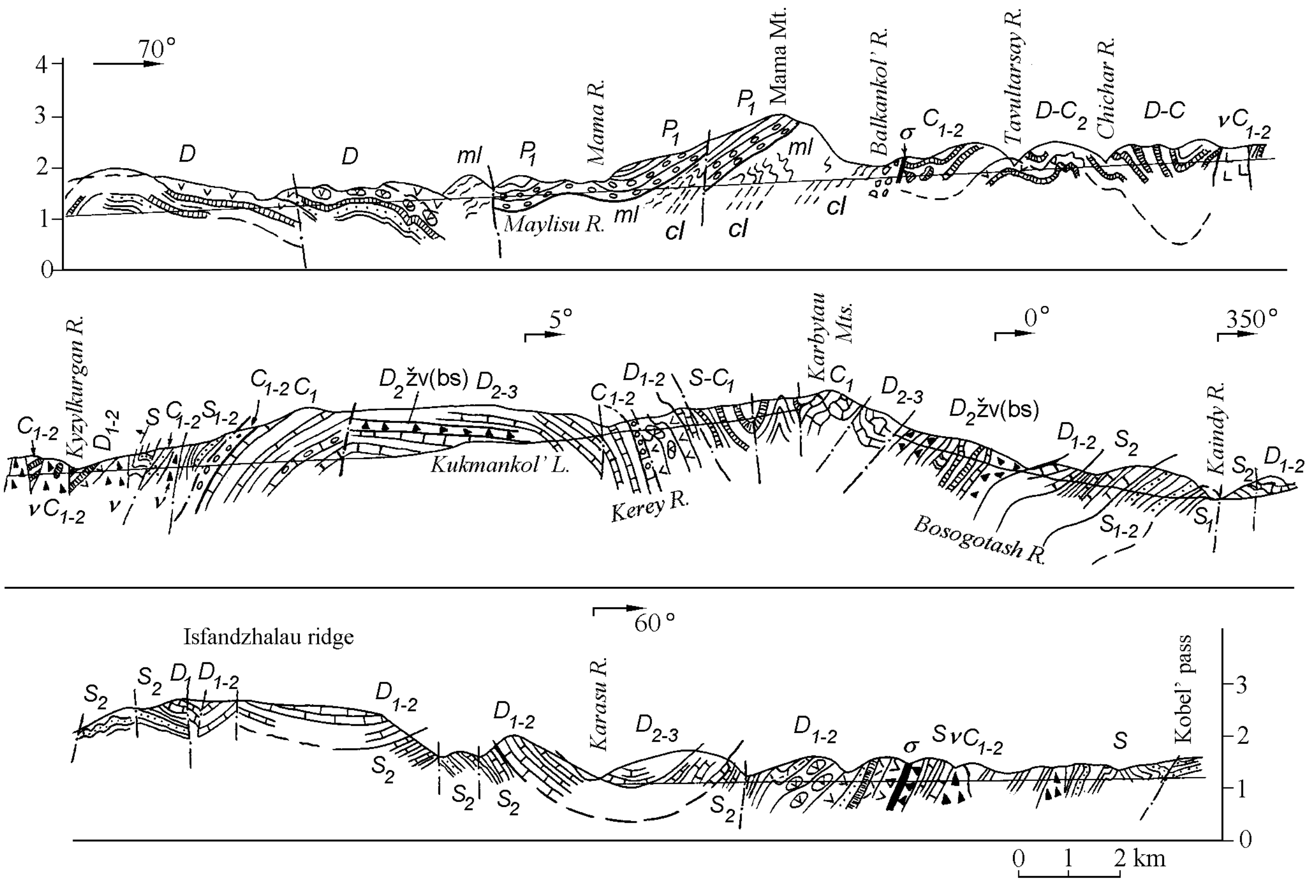

Figure 8. The geological section across the Baubashata mountain group along the Mailisu, Seresu, Kerei, Bosogotash, and Karakul River valleys (see Figure 7).

There are two types of synclinoria in the area of the South Tien Shan. One of them includes fairly wide synclinoria (15–20 km). In the cross-section, these generally negative structural features are open arc-shaped synclines composed mainly of Lower and Middle Paleozoic rocks and less abundant molasse. The small complicating folds and faults produce a divergent structures, a fan, open upward. These are the Aravan, Okhna-Taldyk, Zaamin, and Fan-Margib synclinoria (Figures 6, 19, 17, and 18). The other morphological type is represented by comparatively narrow (3–5 km) structural features that accompany the zones of deep faults composed mainly of young Late Paleozoic rocks of flysch-molasse and molasse composition and of Mesozoic-Cenozoic carbonate and clastic rocks. The small folds and faults produce a synvergent structure, a fan, open downward. These are the Uchkurgan, Surmetash, Daraut-Turkestan, Kshtut-Urmetan, and Ziddy-Karakul synclinoria (Figures 20–30).

The analysis of the folding morphology in the synclinoria shows that the most intensive varieties are restricted to the synclinoria that are located in the axial part of the fold system (Figures 6, 20, 21, 24, and 25). The synclinoria show the predominance of simpler large forms at their edges, the small folding complicating them growing simpler of vanishing (Figures 17, 19, 26–30). The average values of the excessive length factor λ of the layers (Figure 35) diminish in the same direction (from 1.87 to 1.42). Folding is also modified in the synclinoria themselves, the folding being simpler in the cores than in the limbs (Figures 6, 17–21, 24, 27, 28, and 30). These morphological heterogeneities are reflected in the MFC values. The fine folding grows more complex also along the synclinoria trends toward the centroclinal closures or toward the hinge rising (Figures 6, 17, 20, 21, 24, 31, 32, and 36). Some individual large folds, for instance, the first-order synclines, forming the cores of the synclinoria, are arranged en echelon relative to one another. On the whole, there is a paragenetic relationship between the divergent-type synclinoria, the nappe outliers located in them, and the nappes, as well as between the narrow "synvergent" synclinoria with the known deep fault zones [*Zamaletdinov et al.,* 1968; *The problems...,* 1976].

To sum up, our qualitative and quantitative analyses of the morphology of the plicative structural features have re-

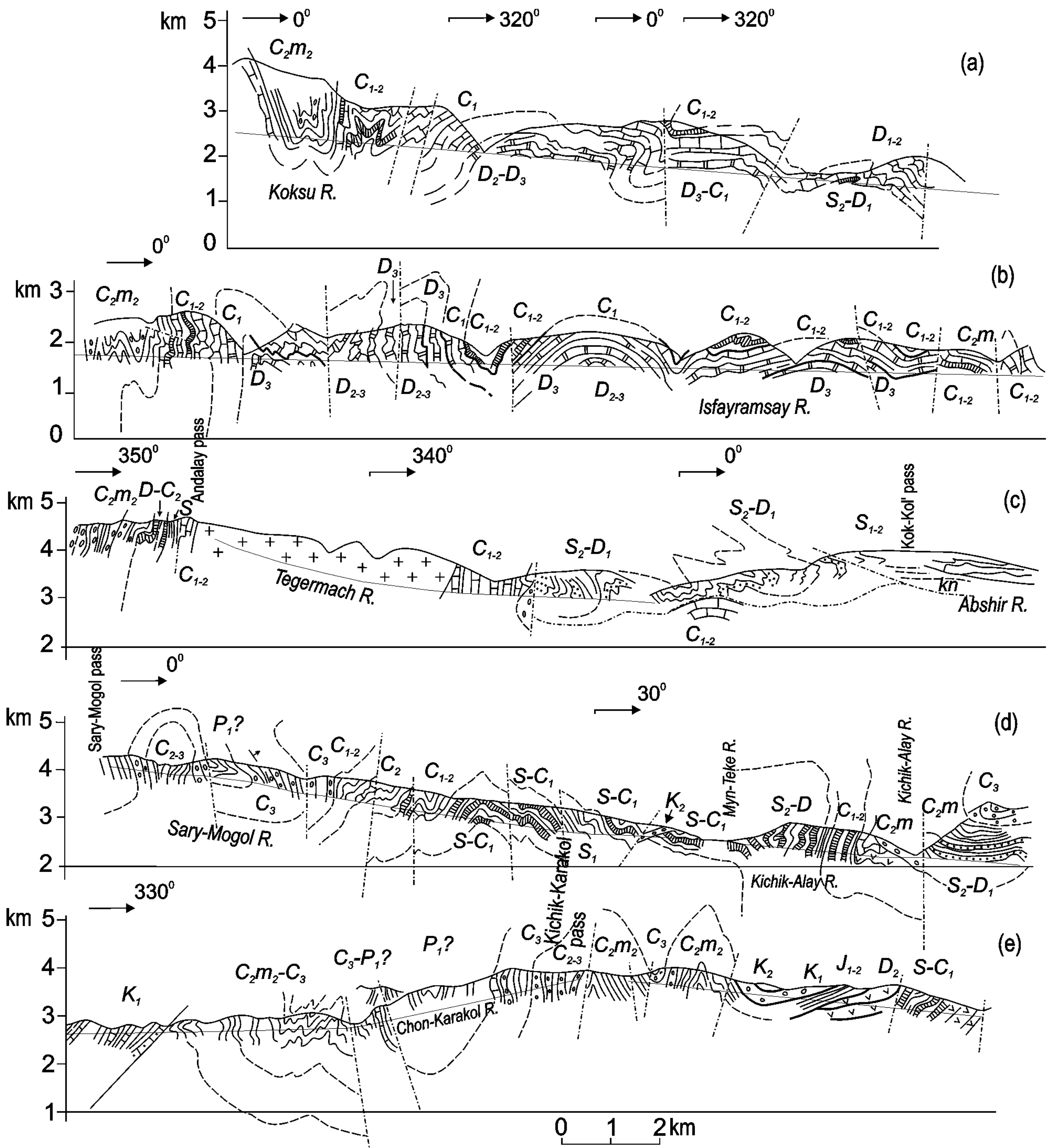

Figure 9. Geological sections across the Kichikalai: (a) in the upper reaches of the Shakhimardan and Koksu rivers; (b) along the Isfairamsai R. Valley; (c) in the upper reaches of the Apshirsai and Tegermach R. Valleys; (d) along the Kichikalai (east) and Sary-Mogol (north) rivers; (e) in the upper reaches of the Chalkuiryuk R. and along the valley of the Chon-Karakol River. See Figure 6 for the legend of these and other geological sections.

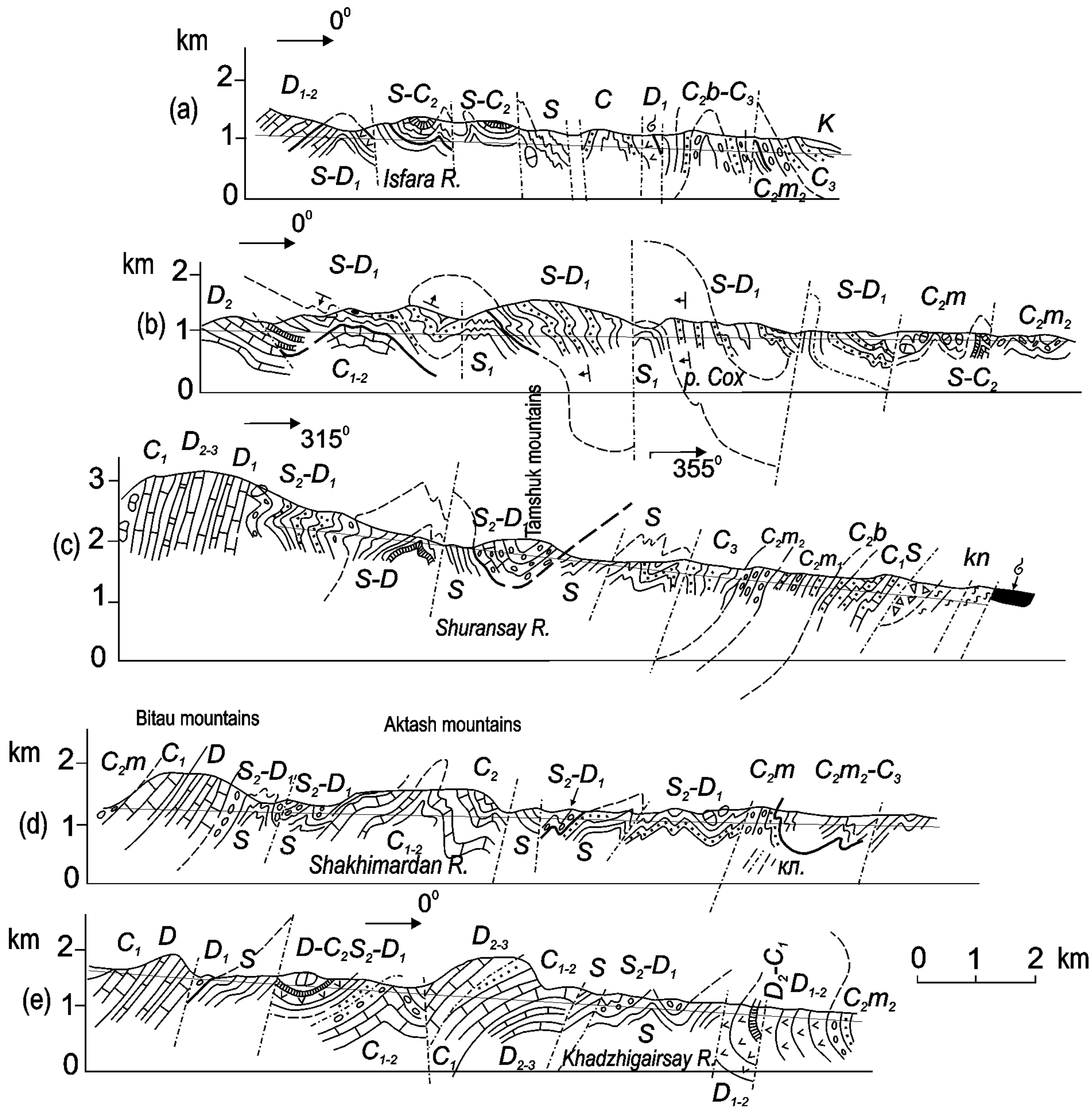

Figure 10. Geological sections for the Kauzan (southern segments of the sections) and for the Uchkurgan Synclinorium (northern segments of the sections): (a) along the Isfara R. Valley; (b) along the Sokh R. Valley; (c) along the Shuransai R. Valley; (d) along the Shakhimardan R. Valley; (e) along the Khodzhagairsai R. Valley; (f) along the Isfairamsai R. Valley; (g) along the Abshirsai R. Valley; (h) along the Kirgizata R. Valley, and (i) along the Akbura R. Valley.

vealed that the folding grows simpler from the axial parts of the fold systems to their margins both in the anticlinoria and in the synclinoria. The typical holomorphic folding variety (MFC = 0.6–1.0) is replaced in the periphery by simpler forms up to the typical intermediate form (FMC = 0.1–0.6). As demonstrated above, the coefficient of the excessive length of the layers (Tables 1 and 2; Figure 35) decreases generally jumpwise rather than gradually. As to the anticlinoria, the folding in the axial parts of the fold systems shows a higher morphologic complexity, as compared to the neighboring synclinoria. This regularity is violated only in the zones of box-shaped folding and in the areas of

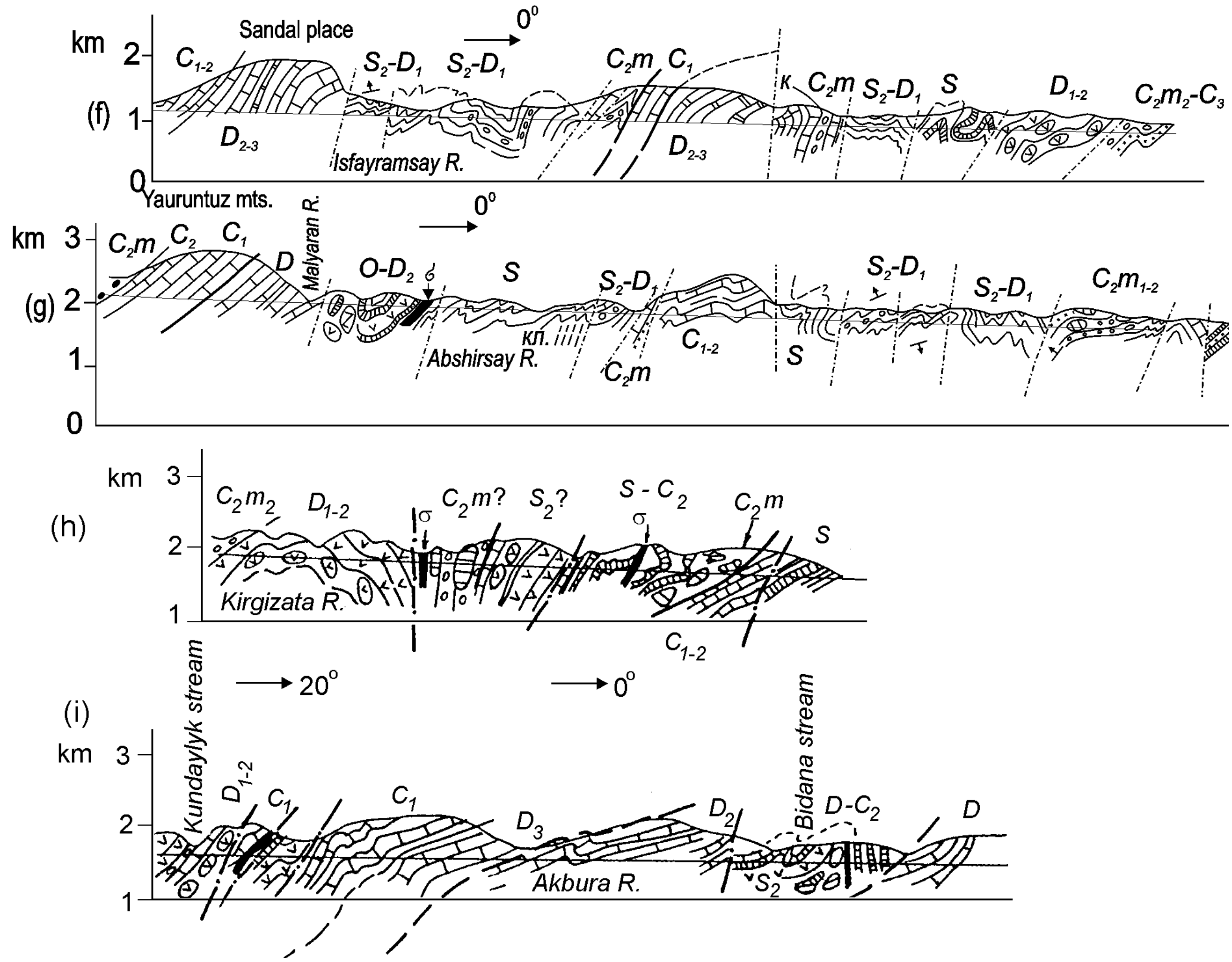

Figure 10. Continued.

wide nappe development. Some anticlinoria and synclinoria show that the rocks in the cores show a simpler structure than those in the limbs.

Changes in the morphological tension of small folds have been also traced along the strikes of the large fold zones. Relatively simpler patterns are observed at the periclinal closures and from the centroclines and hinge rises toward the central parts. Therefore the holomorphic folding grows periodically simpler and more complicated along the strikes of the axial zones of the system. In the regions of a simpler structure the folding loses its similarity with anticlines and synclines and acquires the elements of a morphological similitude with an intermediate pattern.

The distribution of the anticlinoria and synclinoria of both types in the fold system showed a symmetrical and normal pattern, and the fold system can be ranked as a complex meganticlinorium (Figures 31, 36, and 37).

The fold system of the South Tien Shan shows a zonal pattern of the distribution of the longitudinal faults of various morphological types. The marginal structural zones, both the anticlinoria and synclinoria, are disturbed mainly by upthrow faults and overthrusts which reflect the environment of horizontal shortening (by 10–30%), normal to the strike of the fold system. The axial parts of the Zeravshan-Turkestan, Khodzhaachkan, and Kichikalai anticlinoria are dominated by normal faults corresponding to the environment of vertical compression and 10 to 20% submeridional horizontal extension. The narrow fault-bordering synclinoria are dominated by upthrow faults and overthrusts both in the wings of the meg and in its axial parts. These areas are dominated by horizontal compression and 10- to 50-percent reduction. Therefore, the zones of fault development, reflecting the environment of reduction, are replaced repeatedly by the zones with breaks arising in the extension environment.

These estimates, reflecting the conditions of relative reduction or extension, vary greatly from place to place, pro-

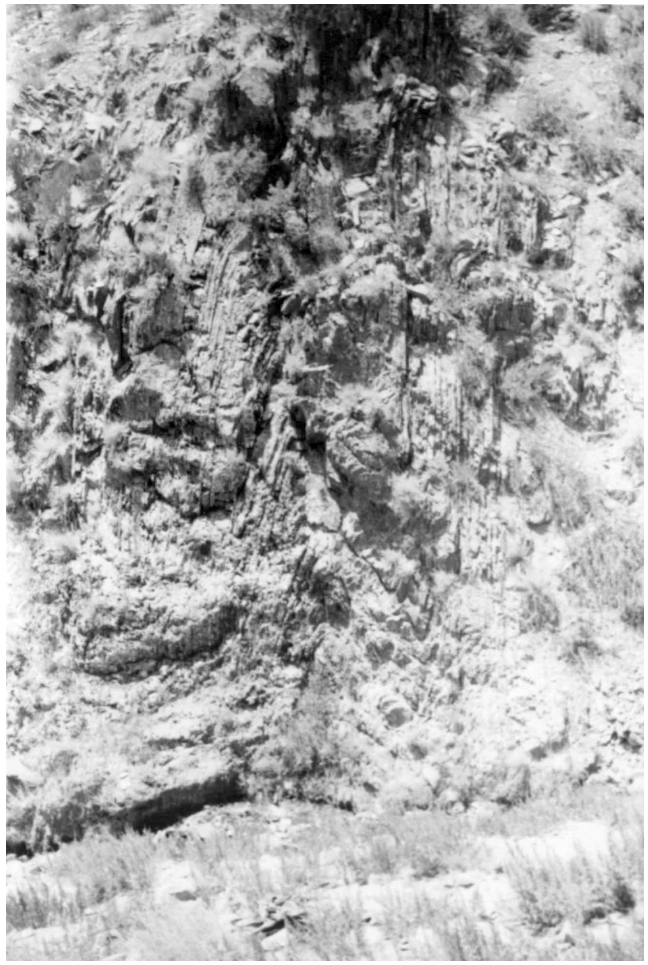

Figure 11. Conjugated inclined small z-shaped folds, not more than a few meters in size, in a Lower Silurian thin-bedded argillite and sandstone sequence (the upper reaches of the Tegermach River, the

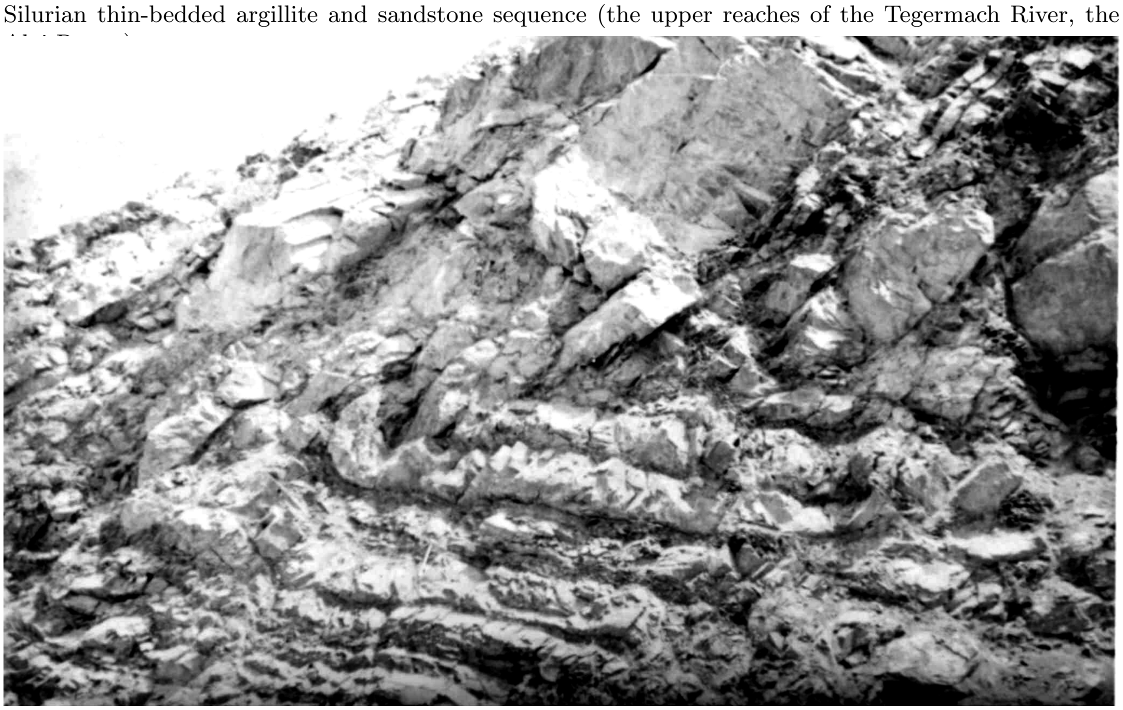

Figure 12. A recumbent Upper Devonian limestone anticline (in the Shakhimardan R. Valley, Alai Range).

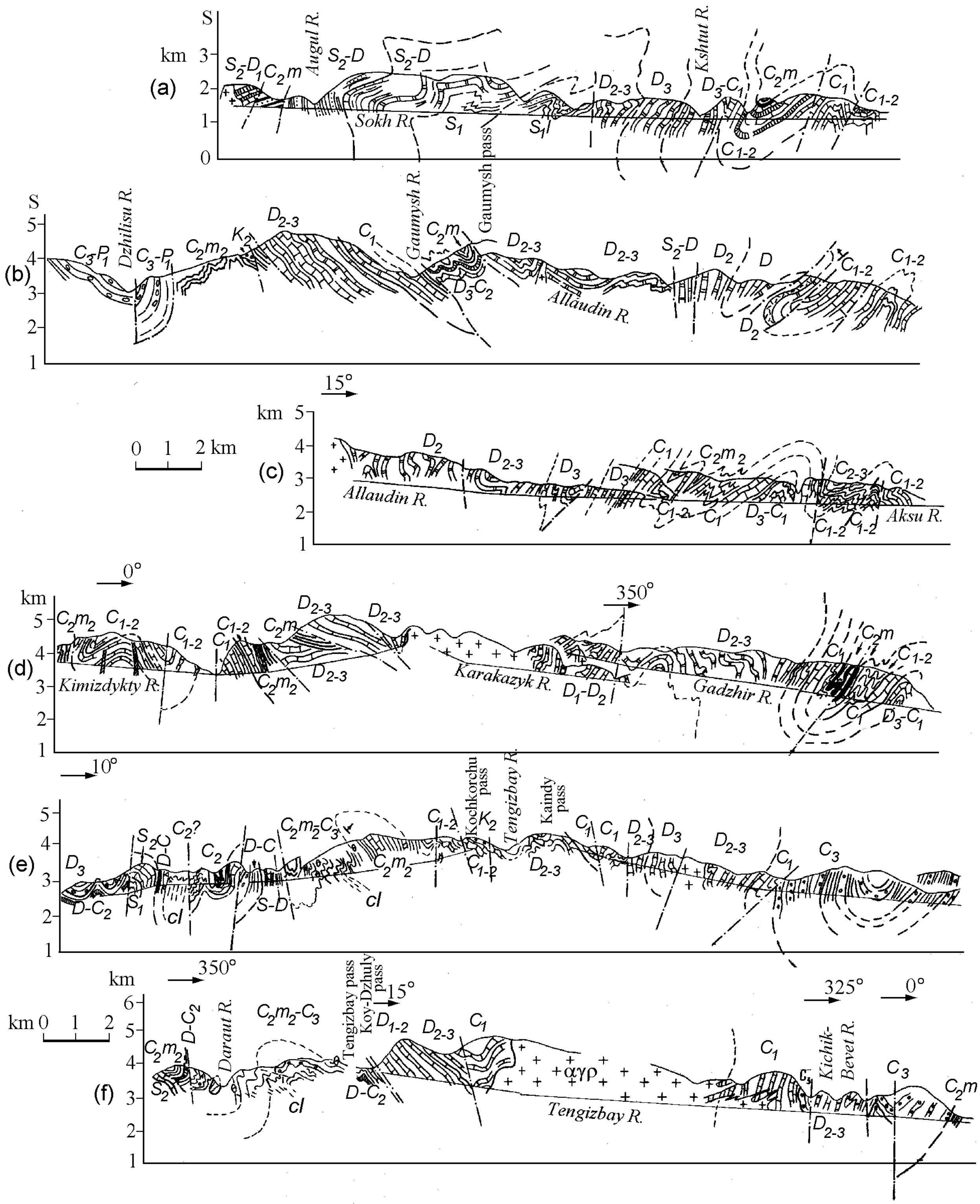

Figure 13. Geological sections across the Khodzhaachkan along the valleys of the Sokh R. (a), of the Alauddin R., across the Gaumysh Pass (b), along the Aksu-Alla-Udin R. Valley (c), along the Gadzhir-Karakazyk-Kimizdykty R. Valley (d), along the Kaindy-Kochkorchu R. Valley (e), and along the Tengizbai R. Valley (f).

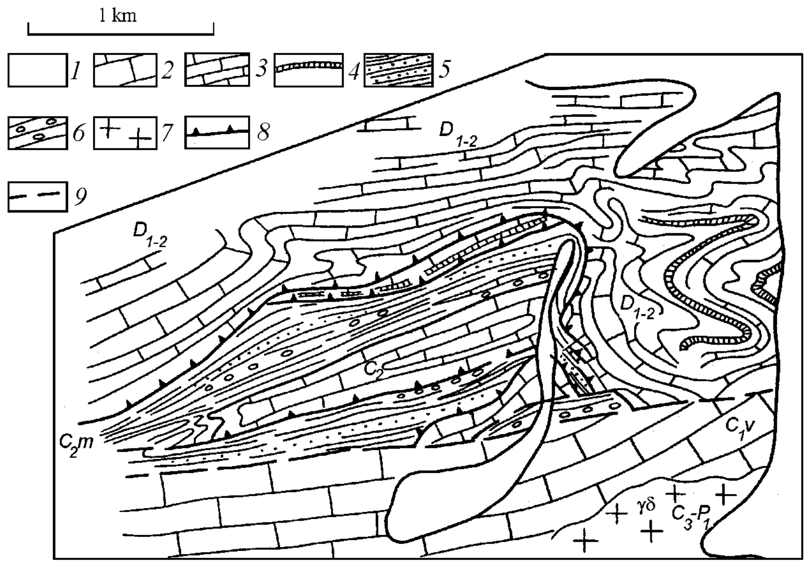

Figure 14. Schematic geological map of the southern limb of the Khodzhaachkan in the upper reaches of the Kainda R. (1) Quaternary alluvial deposits; (2) Visean massive-bedded limestone, Lower Carboniferous; (3) Lower-Middle Devonian thin-and medium-bedded limestone and dolomite; (4) chert interlayers; (5) Middle Carboniferous (Moscovian) sandstone, siltstone, and shale; (6) conglomerate interbed; (7) Late Carboniferous-Early Permian granodiorite; (8) overthrust; (9) other faults.

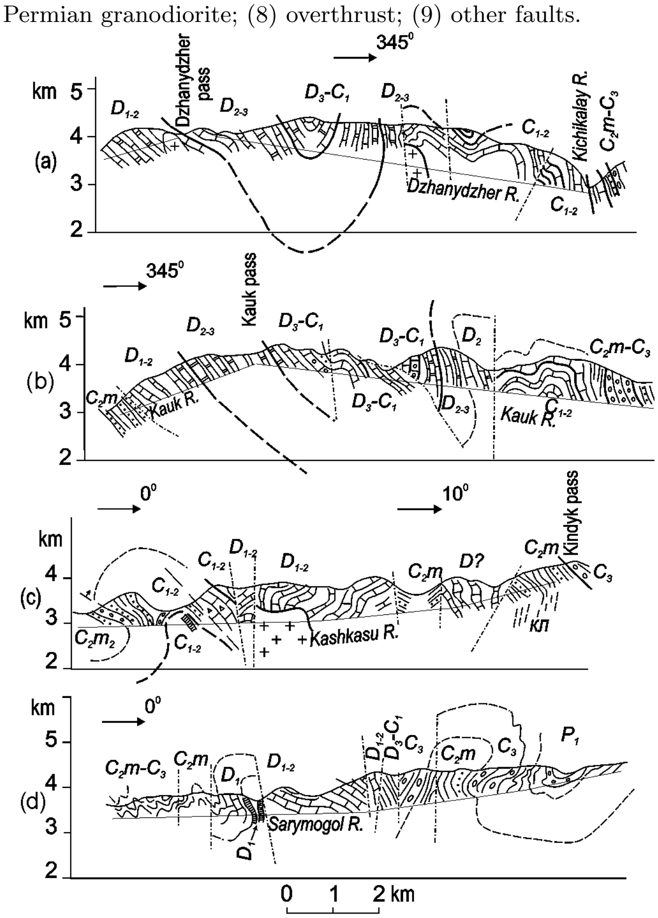

Figure 15. Geological sections across the Kulgedzhile along the Dzhanydzher (a), Kauk and Kavak (b), Kashkasu (c), and Sarymogol (southern) River Valleys (d).

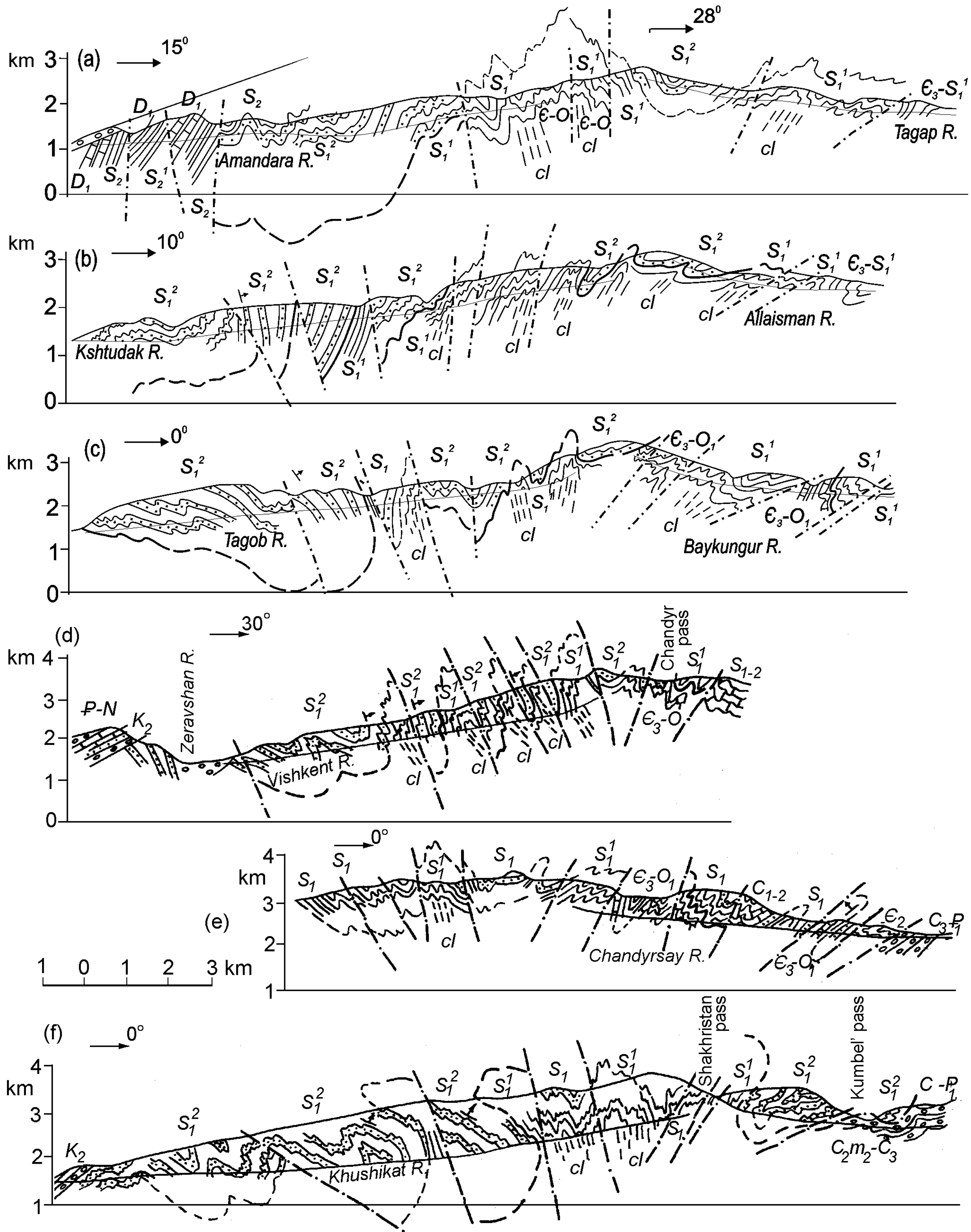

Figure 16. Geological sections across the Zeravshan-Turkestan along the valleys of the Amandara and Tagap rivers (a), the Kshtudak and Allaisman rivers (b), the Tagob and Baikungur rivers (c), the Vishkent R. (d), the Chandyrsai R. (e), and Khushikat and Ortokul rivers (f).

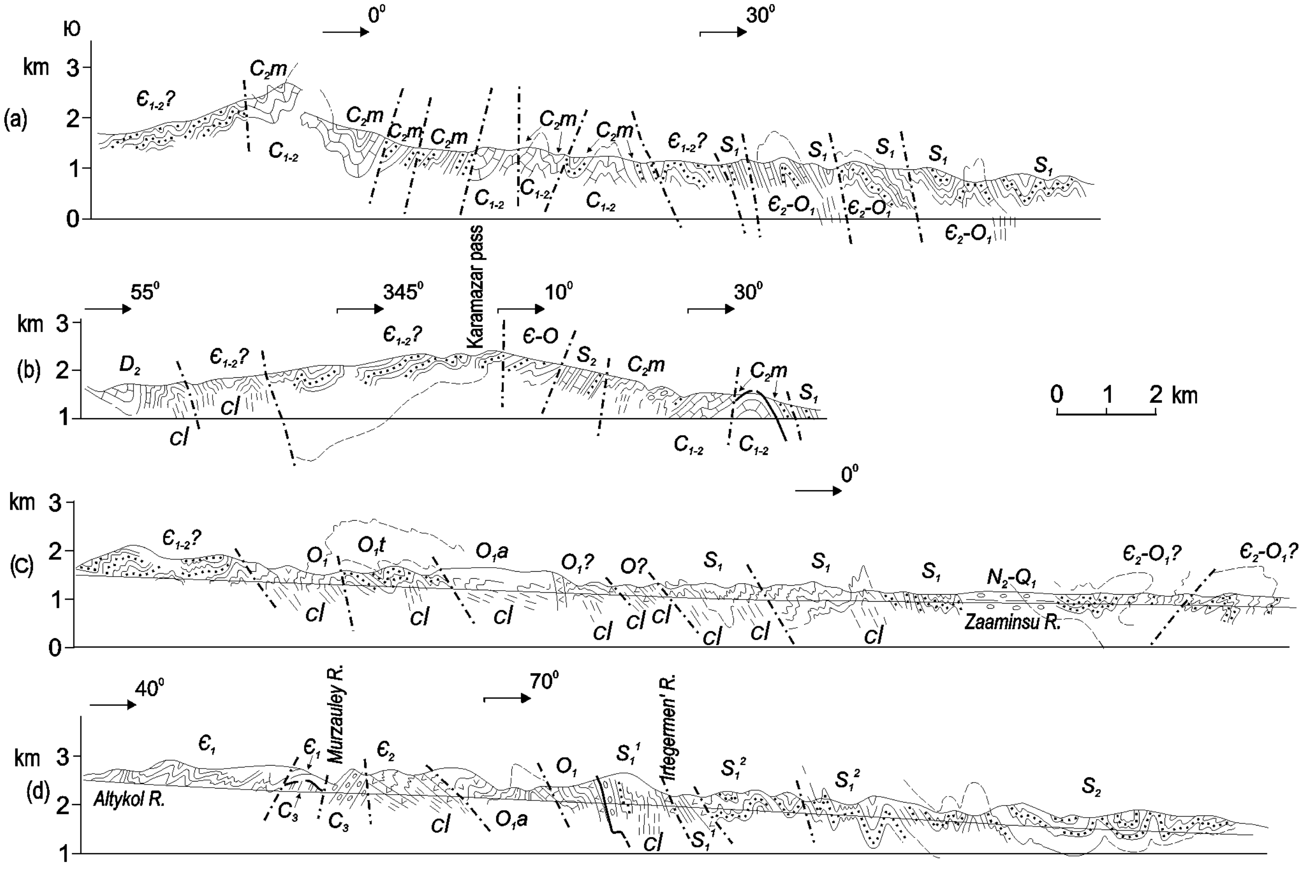

Figure 17. Geological sections across the Malguzar anticlinoria and the Zaaminsu synclinorium along the valleys of the Uab-Ravat R. (a), the Karamazar R. and in the area of the Karamazar Pass (b), along the valleys of the Zaaminsu and Ettkichu rivers (c), and along the valley of the Altylkol R. (d)

ducing transverse zones of a greater or smaller reduction, traceable across several neighboring anticlinoria and synclinoria.

The analysis of the largest Middle Paleozoic angular unconformities in the Southern Tien Shan, recorded at the end of the Late Silurian and in the Late Devonian [*Dovzhikov,* 1976; *Kukhtikov,* 1968; *Porshnyakov,* 1973; *Rogozhin,* 1977; *Sinitsyn,* 1960], suggests that the early folding phases had mainly involved the zones that exist now as anticlinoria. At the same time, highly discordant relations between the rock sequences have been reported there only for the boundary between the Middle and Late Paleozoic [*Dovzhikov,* 1976; *Kukhtikov,* 1968; *Masumov et al.,* 1978; *The problems...,* 1973; *Rogozhin,* 1977; *Sinitsyn,* 1960; *The tectonics...,* 1989].

On the other hand, the orogenic epi-Hercynean structural

Table 2. Average values of the coefficient of the excessive length (λ) of the layers for the South Tien Shan synclinoria

Sample	The name of synclinorium	An average value of λ total	The number of evaluated sections	An average value of λ Alpine	The number of evaluated sections
1	Aravan	1.42	1	1.2	1
2	Uchkurgan	1.65	2	1.5	2
3	Okhna-Taldyk	1.67	4	1.3	1
4	Surmetash	1.87	6	1.33	1
5	Daraut-Turkestan (Kurganak)	1.59	6	1.52	2
6	Kshtut-Urmeta	1.70	5	1.5	3
7	Fan-Margib	1.54	7	1.49	3
8	Ziddy-Karakul	1.45	5	1.33	2

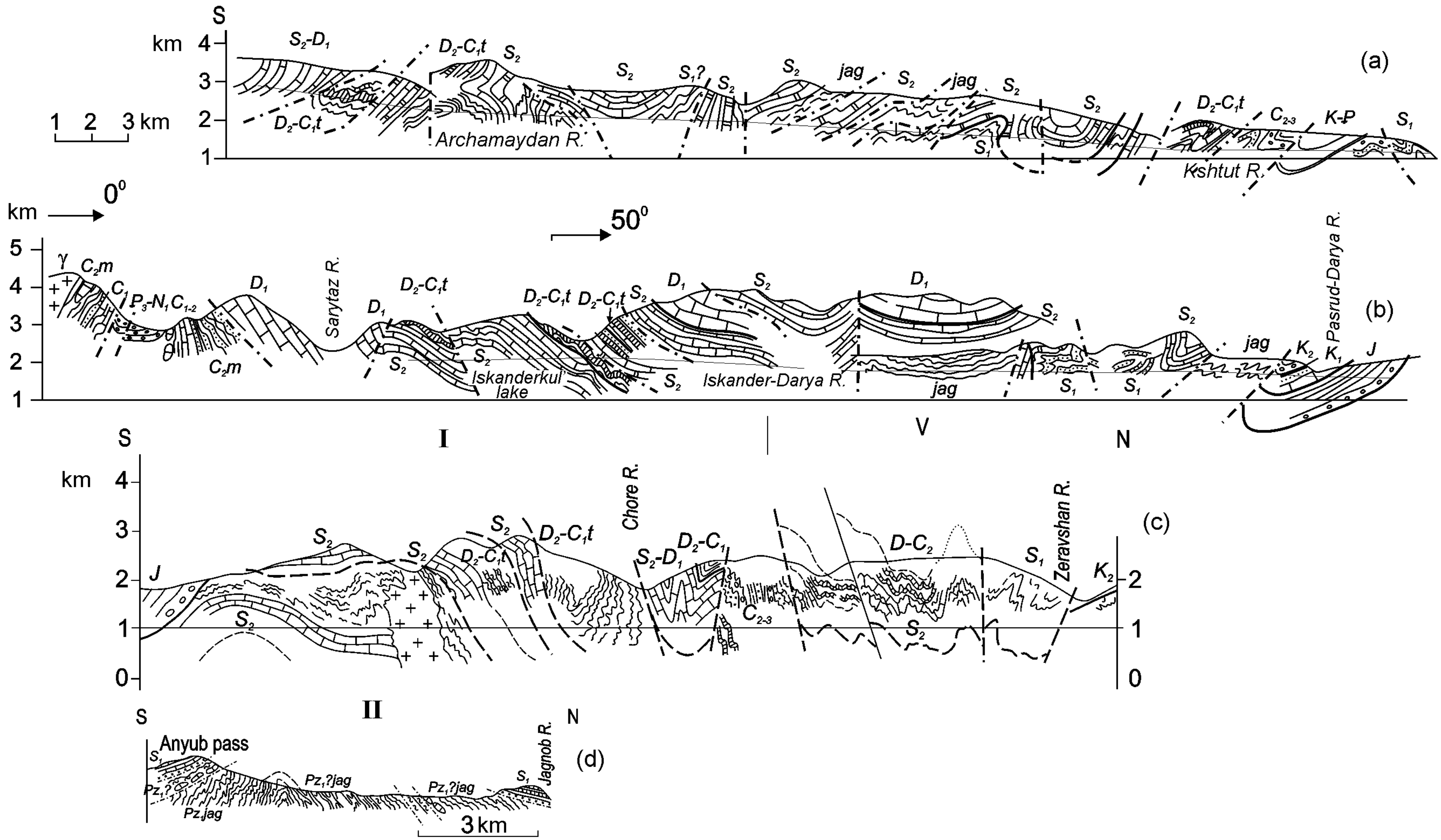

Figure 18. Geological sections across the Zeravshan-Gissar structural zone along the Kshtut-Archamaidan R. (a), and Iskander-Dariya R. (b) valleys; the Zeravshan Range (I) and the Kshtut-Urmeta synclinorium (V) along the Fandariya R. Valley (c), and the Gissar (II) along the Anzob R. Valley (d). Anticlinoria: (I) Zeravshan Range, and (II) Gissar Range; (III) Fan-Margib synclinorium, (IV) Ziddy-Karakul synclinorium.

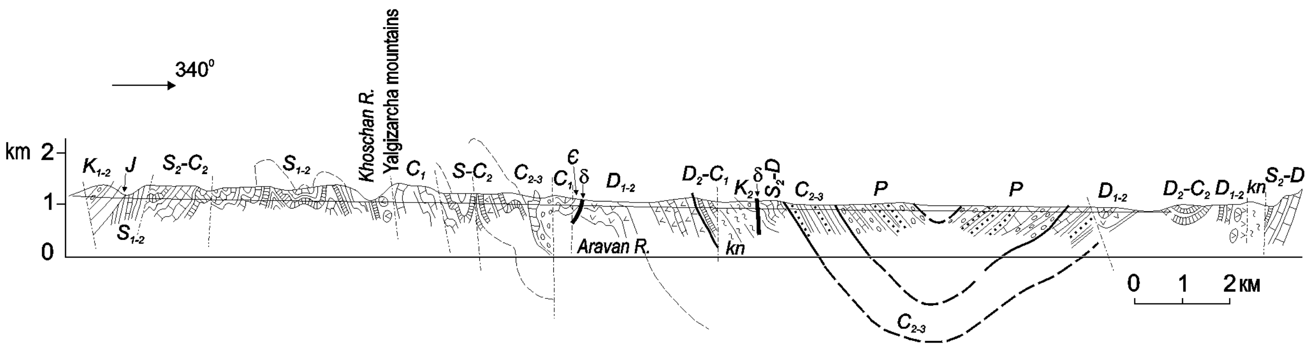

Figure 19. Geological section across the Aravan synclinorium along the Aravan River valley.

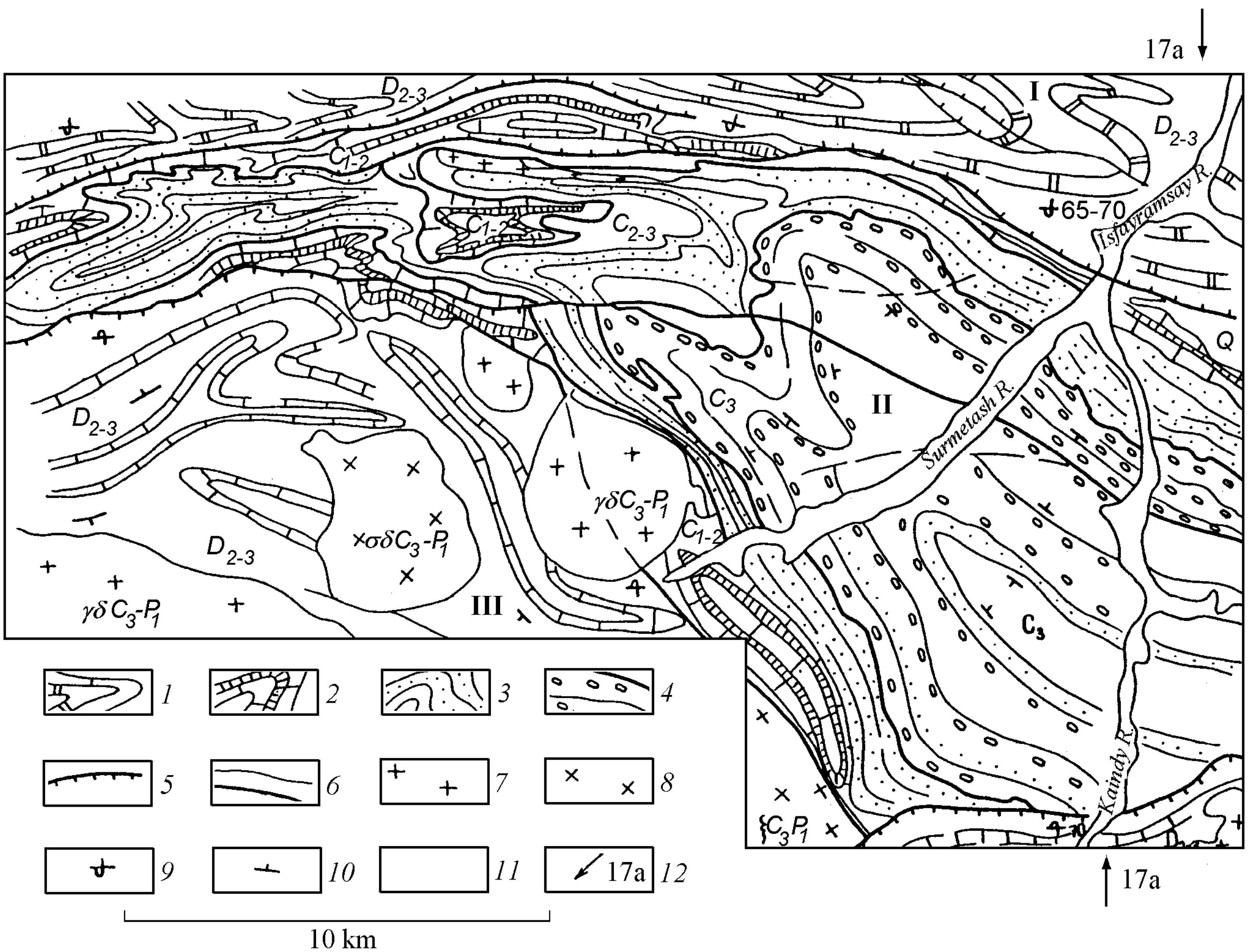

Figure 20. Schematic geological and structural map of the western pericline of the Surmetash synclinorium. (1) Middle and Upper Devonian dolomite and limestone; (2) Lower-Middle Carboniferous (C_2b); (3) sandstone and siltstone with interbeds of Middle (Moscovian) and Upper Carboniferous rocks; (4) Upper Carboniferous conglomerate and gravelite; (5) reverse fault; (6) strike-slip fault; (7) granite; (8) alkalic syenite; (9–10) dip directions: (9) overturned, (10) normal; (11) Quaternary alluvium; (12) line of geological section (see Figure 21a). (I) Kichikakalai synclinorium, (II) Surmetash synclinorium, (III) Khodzhaachkan anticlinorium.

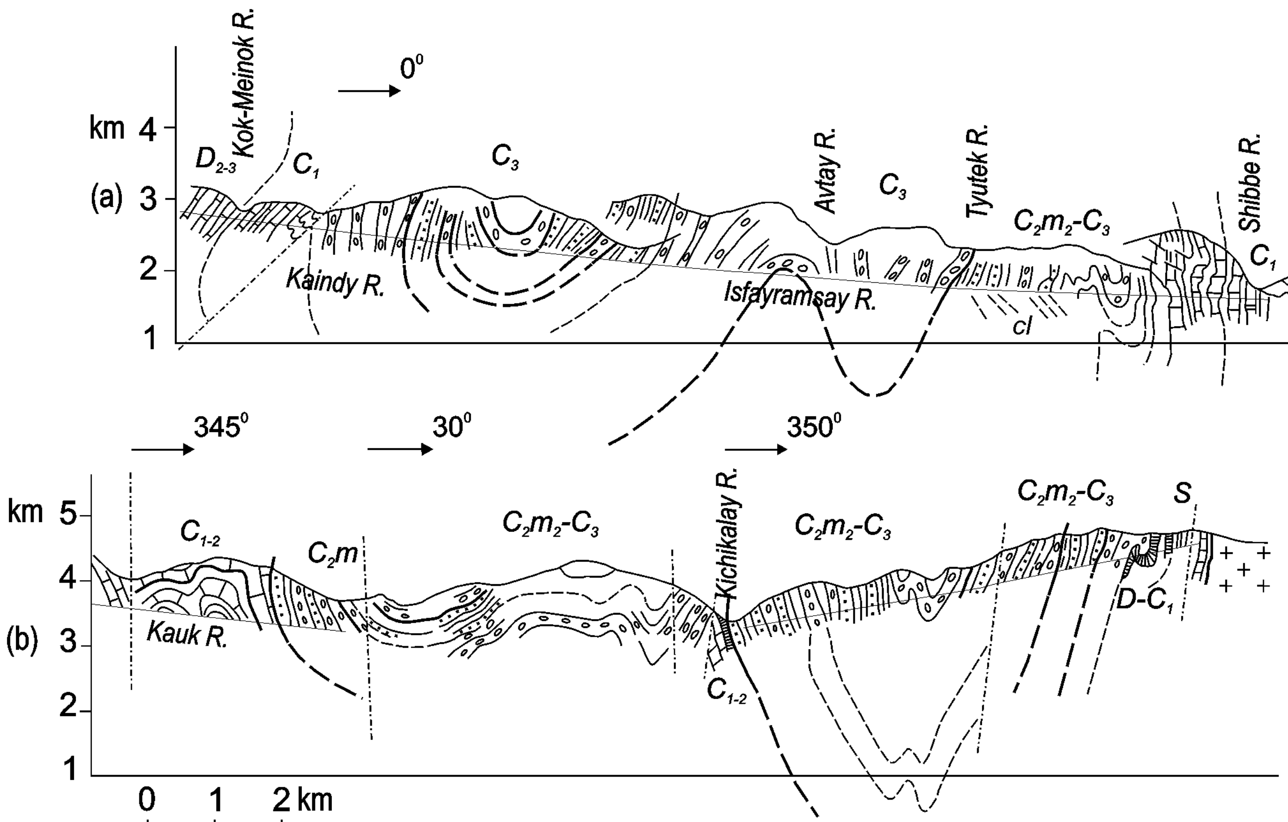

Figure 21. Geological sections across the Surmetash synclinorium along the valleys of the Isfairamsai and Kainda Rivers (a) and along the valleys of the Andalai, Kichikalai and Kauk Rivers (b).

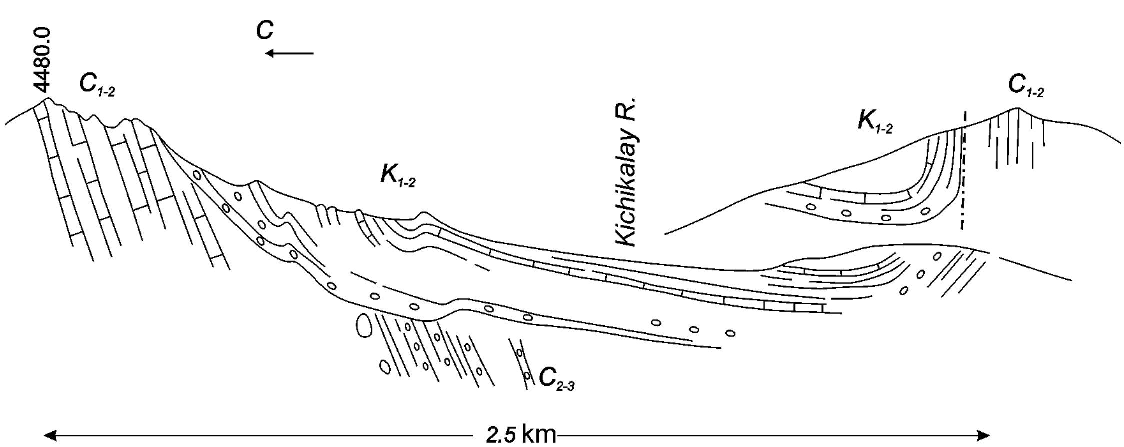

Figure 22. A section across a synclinal fold composed of Cretaceous rocks at the eastern Belalma R. divide area and in the sides of the Kichikalai R.

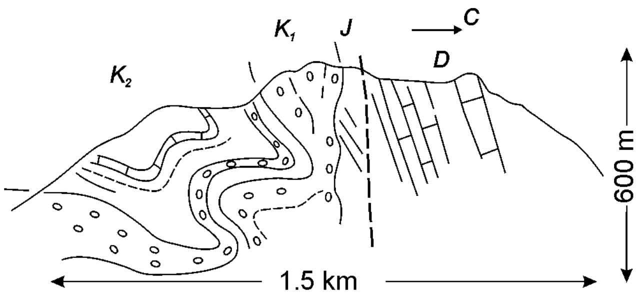

Figure 23. The shape of a fault-related syncline in the Mesozoic rocks of the Daraut-Turkestan synclinorium at the right side of the Tengizbai River upper reaches (Tengiz Syncline).

styles of the large anticlinoria and synclinoria differed significantly as well. The Late Paleozoic molasse sequences, characteristic of the synclinoria, are absent in the anticlinoria. One can see that the anticlinoria and synclinoria of the morphologic types, mentioned above, differ not only in the complexities of their folding, but also in their geological history. The anticlinoria experienced early folding movements during the pre-Early Devonian and pre-Visean folding phases, existing at the same time as uplifts during the orogenic phase. The synclinoria were mainly not involved in the early folding, and remained as residual molasse basins during the Late Paleozoic orogeny and were involved in the folding process only at the very end of the Hercynian cycle.

As has been mentioned above, the nappe-and-fold structure of the Baubashata mountain node was discussed com-

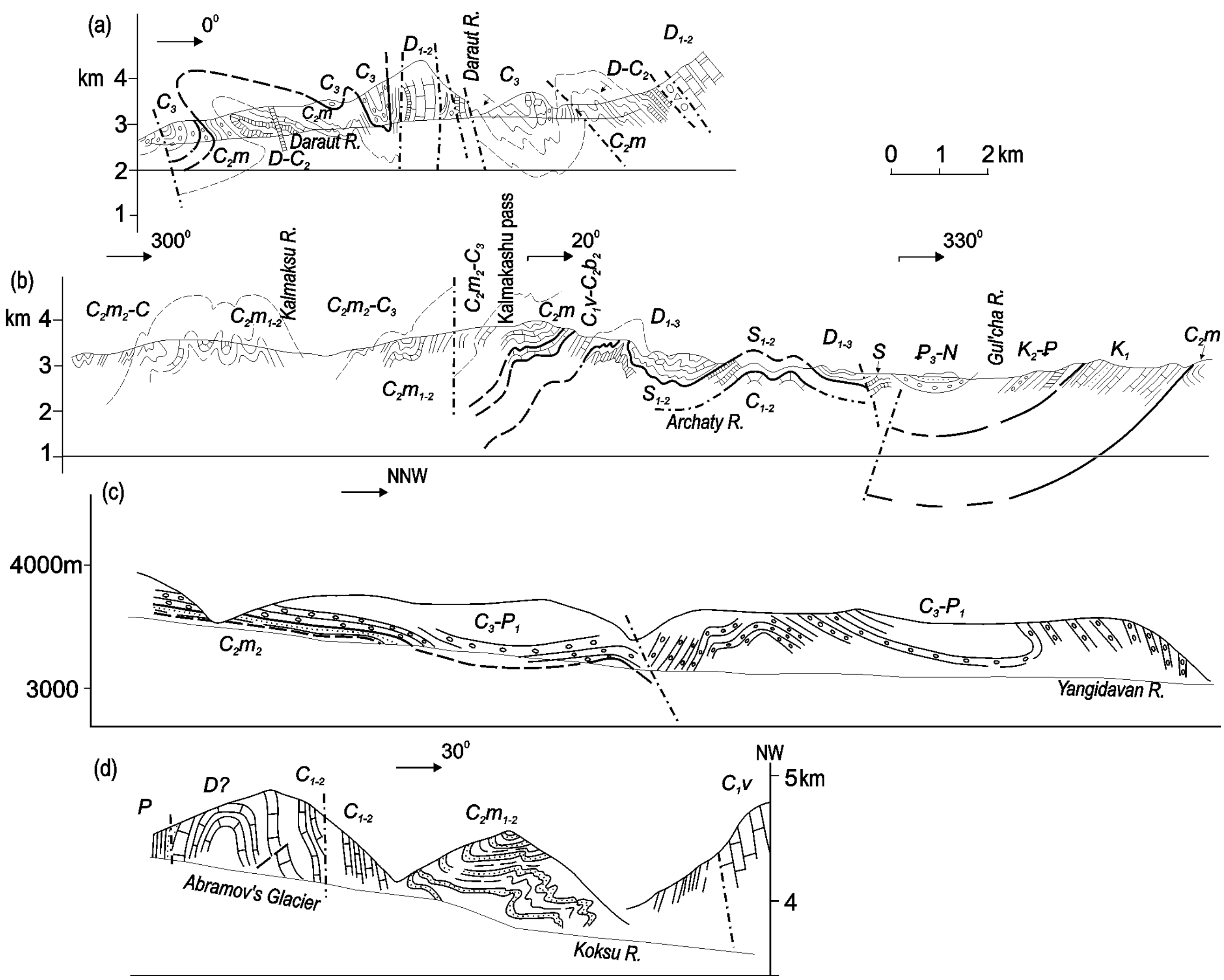

Figure 24. Geological sections across the Daraut-Turkestan synclinorium: (a) along the Darautsai R. Valley; (b) along the Archarty R. and Kalmaksu R. Valleys; (c) along the Yangidavan R. Valley; and in the upper reaches of the Koksu R. Some fragments of this synclinorium structure can be also observed in Figure 13 (sections b, d, and e).

Figure 25. Recumbent disharmonic folds in the condensed section of Devonian–Lower Carboniferous radiolarites (the area of the Gaumysh Pass, Alai Range).

paratively while describing the structure of the other South Tien Shan regions. The Paleozoic rocks of this part of the fold system resembles the respective rocks from the Turkestan-Alai region, differing from the latter in some minor details.

The carbonate rocks of the "shelf" zone occur as an autochthon. They compose the Baubashata core, being exposed in the axial parts of huge anticlinal folds in the eastern part of the mountain node (22 in Figure 7). These mainly carbonate rocks are covered by three tectonic nappes. The lower nappe is composed of the rocks of a condensed siliceous rock sequence, the intermediate nappe consists of volcanic rocks, and the upper nappe, of mostly green metamorphic schists. The tectonic contacts between the allochthonous and autochthonous slabs are easily traceable thanks to the lithological differences of the rocks composing these structural units.

The geological section presented in Figure 8 allows one to trace the large structural units of the allochthon and autochthon, as well as the character of their minor deformations. One can see that the carbonate and volcanic rocks of the autochthon occur as large positive folds. They can

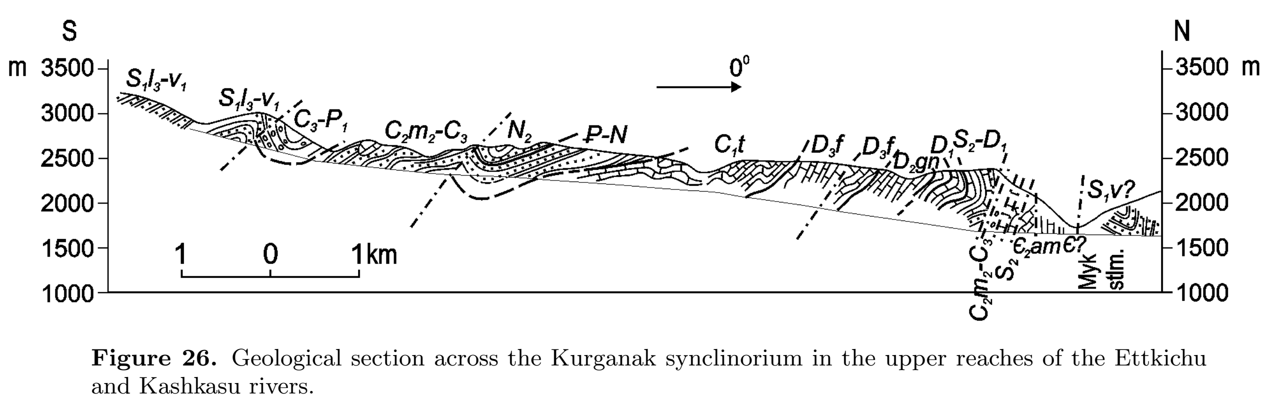

Figure 26. Geological section across the Kurganak synclinorium in the upper reaches of the Ettkichu and Kashkasu rivers.

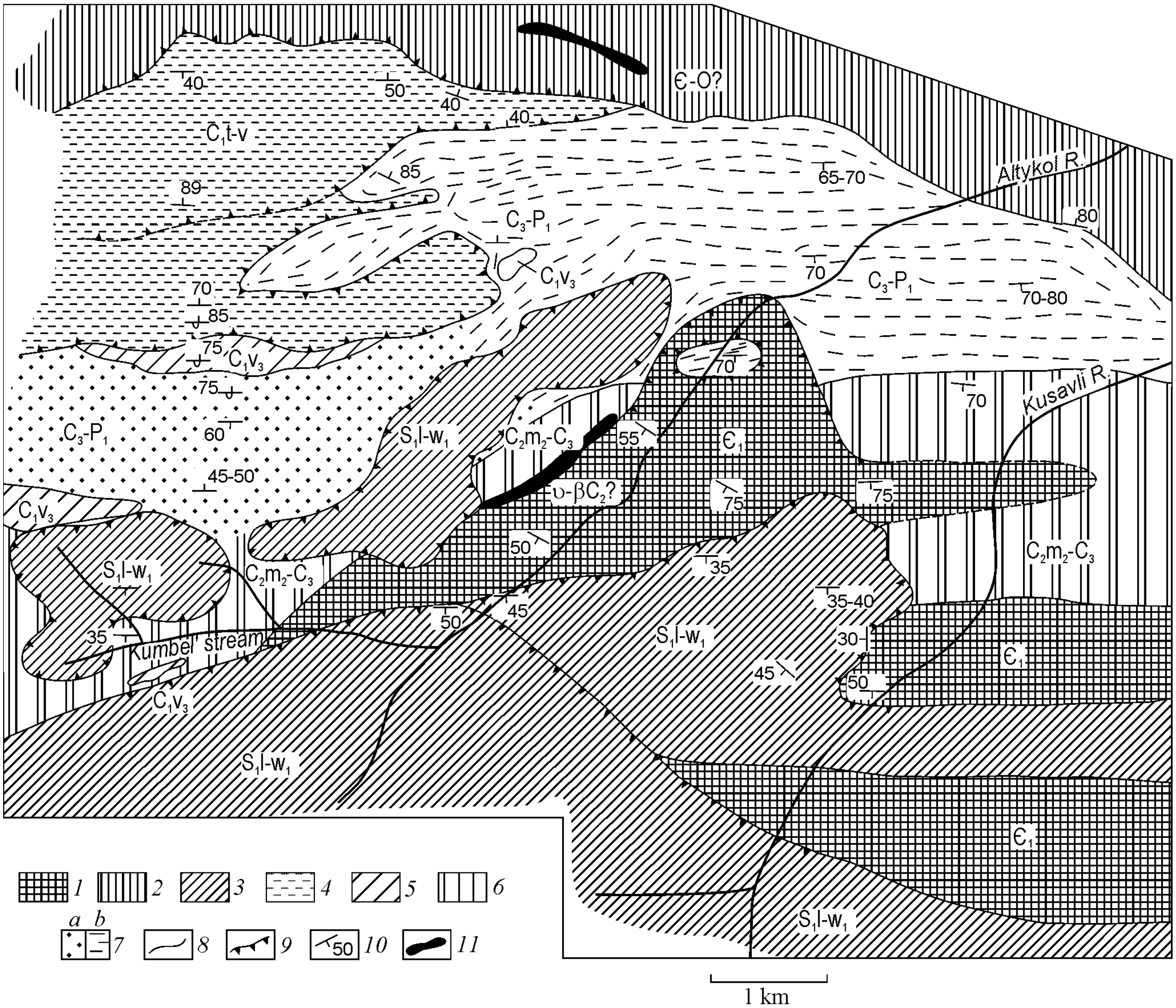

Figure 27. Schematic geological map of the Kurganak synclinorium in the upper reaches of the Altykol and Kusavli rivers [*Rogozhin,* 1977]: (1–7) Paleozoic rocks: (1) Lower Cambrian shale and sandy limestone; (2) Cambrian-Ordovician (?) black shale; (3) Lower Silurian sandstone, siltstone, and shale; (4) Carboniferous (Tournaisian and Visean) limestones; (5) Carboniferous (Visean) limestones; (6) sandstone, siltstone, shale, and phyllite schist with interbeds of Late Moscovian (Middle and Late Carboniferous) conglomerate and gritstone; (7) Late Carboniferous and Early Permian conglomerates: (a) unmetamorphozed, (b) metamorphosed to greenschist and amphibolite facies and crushed; (8) steep fault; (9) overthrust; (10) dip and strike; (11) gabbro diorite dike

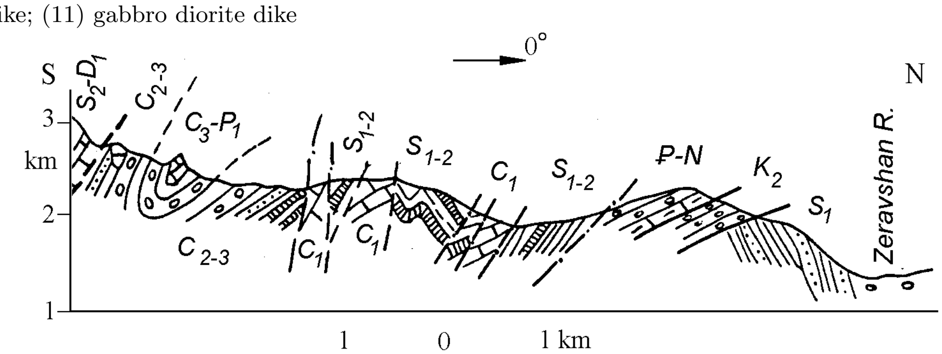

Figure 28. A geological section across the Kshtut-Urmeta synclinorium along the Madm R. Valley.

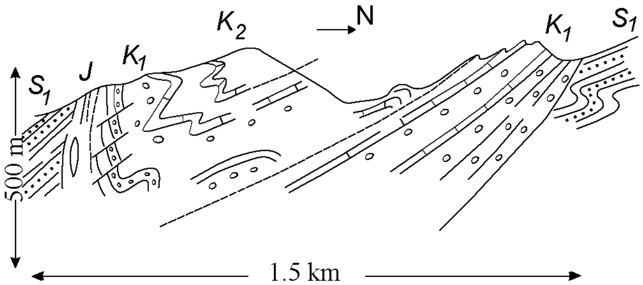

Figure 29. The structure of the Mesozoic and Cenozoic rock sequences in the Kshtut-Urmetan synclinorium along the Krut R. Valley.

hardly be compared with the anticlinoria of the Alai Range, even though they are comparable in size. These are extensive mainly arc-shaped (in cross-section), gentle and open anticlines, 10–20 km wide and 3–6 km high, generally having a sublatitudinal strike. Westward, the carbonate rocks of the autochthone plunge under the allochthon slabs. The large positive structures of the autochthone are poorly complicated by minor folds. The structures of this kind are almost absent in the southern Seresu anticline, and small additional folds in the northern, Kaindy, anticline have the same open and simple form, as the large structural features, complicated by them.

The rocks composing the large tectonic nappes are crumpled to negative folds. Our geological cross-section crossed two of such synclines which can be referred to as synclinoria because of their large forms, namely the Kerei and Mailisui synclines. The core of the Kerei syncline is composed mainly of terrigenous and siliceous rocks, and some minor volcanic rocks, all broken by numerous subvertical faults. This syncline has the form of an open arc in the cross section. There are also some minor complicating folds, both poorly compressed (in the Middle Devonian globular lavas), and very narrow, almost isoclinal (in the Silurian terrigenous and sometimes in younger siliceous rocks).

The rocks of all three allochthonous slabs are developed in the second, Mailisu, syncline. With the general wide and open form of the syncline, the numerous folds complicating it also have mainly an arc-shaped or box-like form. The exceptions are rare narrow compressed folds among the smallest folds of the 4th order. This intermediate folding type shows a very rare vergence. Only some smallest folds and the positions of the relatively large folds of the last generation (3rd order) developed in the green schists enable one to establish some incline of this structural feature to the northeast.

In general, the Baubashata nappes show a significant resemblance with the nappes of the Alai Range even though the folding had been formed in these two regions of compositionally similar rocks

Heterogeneity of the Fold-and–Fault Structure and the Recent Structural Style

We compared the revealed structural heterogeneity of the South Tien Shan region with its recent structural style. Our comparison of the map of the morphologic folding types (Figure 31) with the Neotectonic Map of the Southern USSR, edited by L. N. Polkanov [*Neotectonic map...,* 1971], and with the data reported in [*The active...,* 2000], revealed that many zones of intensive folding, restricted to the anticlinoria of the axial parts of this mountain system are simultaneously the most elevated structural features of the crust (Zeravshan-Turkestan, Khodzhaachkan, and Kichikalai anticlinoria of the Zeravshan Range). Most of the less intensively folded synclinoria are marked in the present-day structure by topographically low areas and areas of recent descent (Okhna-Taldyk, Surmetash, Daraut-Turkestan, Kurganak, Kshtut-Urmetan, Ziddy-Karakul, and, in places, Fan-Margib synclinoria). The synclinoria, especially those of the second, fault-related type, had experienced subsidence earlier, namely, during the Mesozoic, Paleogene, and Miocene time [*Masumov et al.,* 1978; *Nesmeyanov and Barkhatov, 1978; The recent...,* 2000; *The problems...,* 1973].

The study of the fold structures in the Mesozoic and Cenozoic deposits in several synclinoria of the Turkestan-Alai region and the Zeravshan-Gissar zone, both in the narrow fault-related synclinoria (Figures 16, 18, 22–24, 26, 28, and 29) and in the broad open ones (Figure 19), allowed us to compare quantitatively the degrees of the horizontal reduction of these structural features during the Hercynian and Alpine periods of time. We measured the excessive lengths

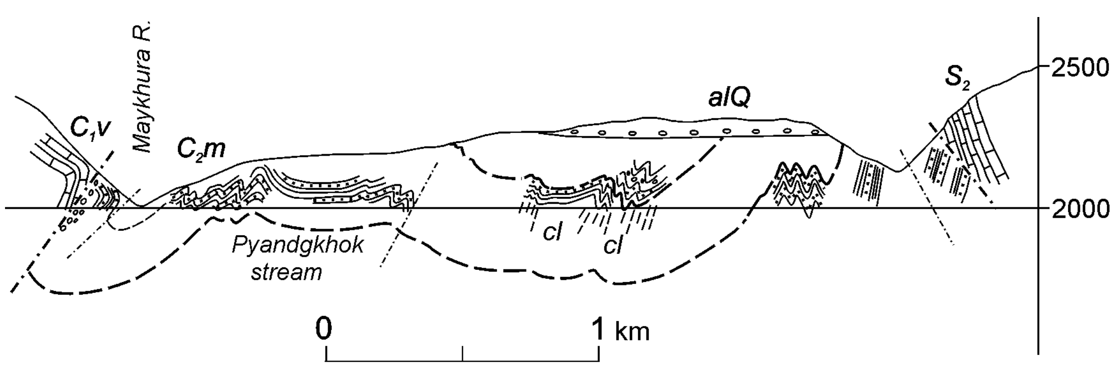

Figure 30. Geological section across the Ziddy-Karakul synclinorium along the Pyandzhhok R. Valey.

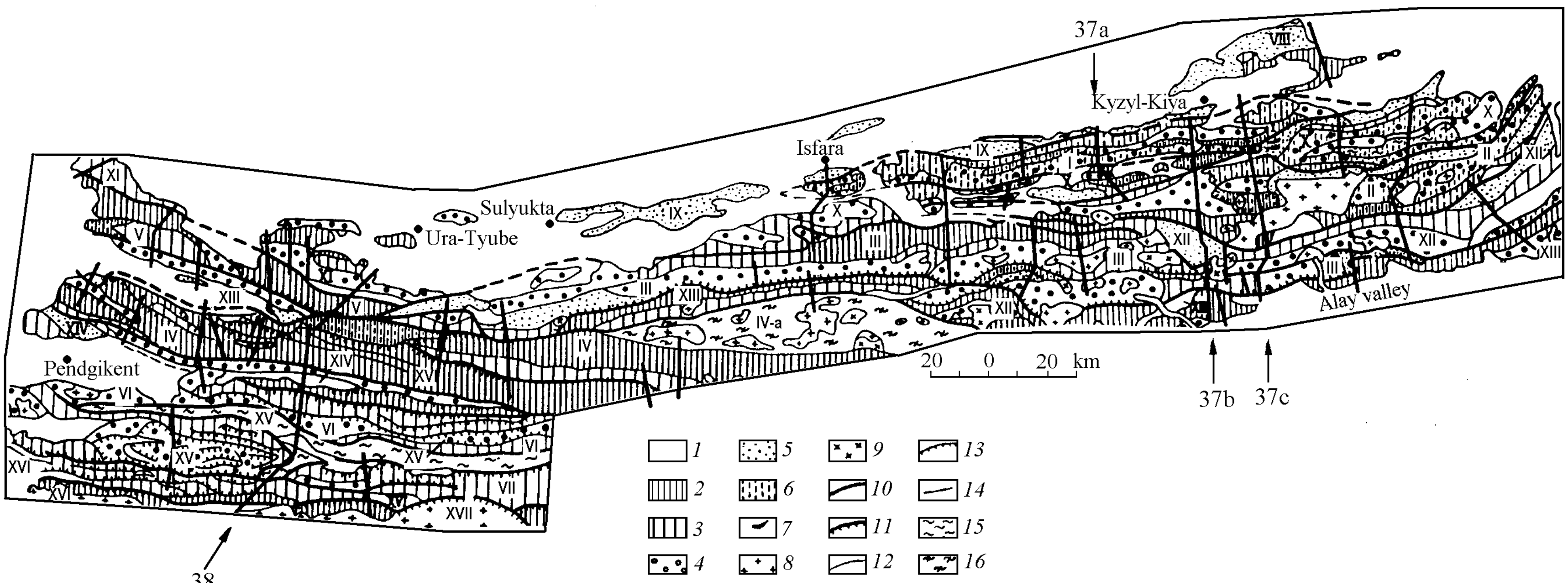

Figure 31. Map of morphological folding types in the central segment of the South Tien Shan region. (1) Mesozoic and Cenozoic rocks; (2–5) zones of different morphologic folding types: (2) compressed, isoclinal, and carinate folds (tightness scale (t.s.)=0.8–1.0); (3) less compressed linear folds (t.s.)=0.6–0.75; (4) arc-shaped and crestlike folds (t.s.)=0.25–0.55; (5) box-like, trough-shaped folds and flexures (t.s.)=0.1–0.2; (6) zones of overthrust structure; (7–9) intrusive rock massifs: (7) ultrabasic rocks, (8) granitoids, (9) alkaline rocks; (10) boundaries of large fold structures (anticlinoria and synclinoria); (11) same, coinciding with regional thrust faults; (12) boundaries between zones of different folding morphology; (13) same, coinciding with thrust faults; (14) lines of geological sections used; (15) greenschist (metamorphic) rocks; (16) metamorphic rocks (crystalline schist, gneiss, greenschist) of the Turkestan metamorphic zone.
Anticlinoria: (I) Kauzan, (II) Kichikalai, (III) Khodzhaachkan, (IV) Zeravshan-Turkestan, (IVa) Turkestan metamorphic zone, (V) Malguzar, (VI) Zeravshan Range, (VII) Gissar.
Synclinoria: (VIII) Aravan, (IX) Uchkurgan, (X) Okhna-Taldyk, (XI) Zaama, (XII) Surmetash, (XIII) Daraut-Turkestan (Kurganak), (XIV) Kshtut-Urmeta, (XV) Fan-Margib, (XVI) Ziddy-Karakul, (XVII) South Gissar structure-formation zone.

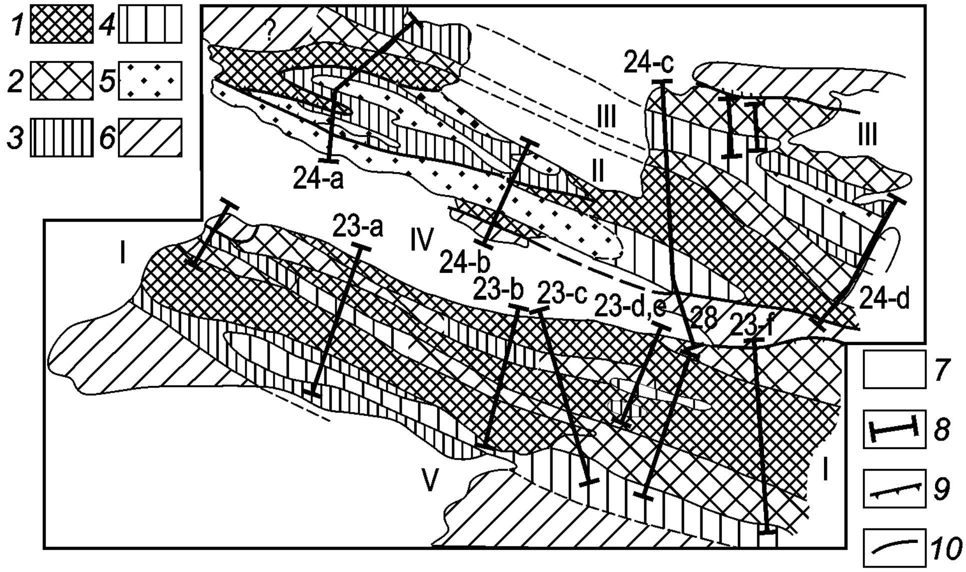

Figure 32. Map showing the distribution of folds with a varying degree of morphologic complexity (m.c.) for the flysch and shale in the western part of the Turkestan Range and the Malgauzar Mountains. The m.c. grades: (1) 1.0–0.95; (2) 0.95–0.75; (3) 0.7–0.6; (4) 0.55–0.45; (5) 0.4–0.3; (6) areas where m.c. grades were not estimated; (7) Mesozoic and Cenozoic rocks; (8) positions of the geological sections used (Figures 16 and 24); (9) normal overthrust fault; (10) other faults. Anticlinoria: (I) Zeravshan-Turkestan, (II) Malgauzar, (III) Zaama, (IV) Kurganak, (V) Kshtut–Urmetan.

of the layers in the folds that had originated in the young deposits and compared them with the lengths measured in the same synclinoria, but in the folded Paleozoic deposits (Table 2). Our comparison of the λ value in the structures of the Hercynian-Alpine and recent deformation revealed that the recent structures had been subjected to somewhat lower compression in the course of folding (Figure 35), even though the horizontal reduction of the layers in the course of the Hercynian-Alpine deformation had been comparable with the value computed exclusively for the Alpine deformation, that is, the recent deformation of the South Tien Shan turned out to be fairly substantial, as has been demonstrated by a different methods [*Yablonskaya,* 1989; *Yakovlev and Yunga,* 2001].

At the same time the fold structure of the Hercynian basement is morphologically much more complex than that in the Alpine rocks. The Paleozoic (including Late Paleozoic) deposits, developed in the central parts of the fold system, show multi-order disharmonic folding which can be classified as a complete morphological variety. The Mesozoic and Cenozoic rocks, developed in the same areas, are dominated by, although closely compressed, but mainly large and simple dislocations.

An important feature is the inherited character of the Alpine deformation at the level of the horizontal reduction of the layers from the Hercynian one in the synclinoria. It appears that the same pattern could be observed in the limits of the anticlinoria, but the Mesozoic-Cenozoic rocks are completely demolished there by the erosion without any significant asymmetry in the style of the horizontal reduction of the anticlinoria and synclinoria across the strike of the fold structure. This means that in the course of the folding formation the external compression of the South Tien Shan did not play any significant role. Both the amount of the horizontal (total and Alpine) reduction, and the morphological folding complexity increase from the margins to the internal zones of the fold system.

The layers of the Alpine rocks filling the narrow fault-related Surmetash, Daraut-Turkestan, Kshtut-Urmetan, and Ziddy-Karakul synclinoria are inclined southward at the angles of 20°–30°. This and often the ramp and half-ramp character of the anticlinoria suggest that the latter developed, during the Alpine deformation period, in the environment of external horizontal compression. The vertical movements of the Alpine period generally inherited the Hercynian structural style and even contributed to the best expression of the fanlike folding vergence at the boundaries between the anticlinoria and synclinoria. The dip angles of the axial surfaces of the folds in the marginal parts of the Zeravshan-Turkestan and Khodzhaachkan anticlinoria grew 10°–30° as a result of the Alpine movements, compared to the vergence of the Hercynian time (Figure 13c, and 16e,h).

Folding Formation Mechanism

The results of this study provided a new view at the structure of the South Tien-Shan Fold System. This system is not a zone of the continuous development of uniform holo-

Figure 33. A photographs showing a tight vertical isoclinal fold in Lower Silurian shale and siltstone (Tagob R. Valley).

morphic folding [*Rogozhin,* 1977, 1986, 1993], as believed before [*Dovzhikov,* 1977; *The problems...,* 1973; *Sinitsyn,* 1960]. Moreover, many different processes contributed to the formation of the present-day appearance of this fold structure during various phases of the evolution of this mobile region. These processes were especially diverse during the Early Hercynian time when the overthrust sheets were formed [*Burtman,* 1973, 1976; *Klishevich,* 1986; *Porshnyakov,* 1973], during the Late Hercynian time, when the "main folding" was formed [*Dovzhikov,* 1977; *Porshnyakov,* 1973; *Rogozhin,* 1977, 1993], and during the recent time when the modern appearance of this fold-mountain region had been shaped [*Chediya,* 1972; *Dzhamalov et al.,* 1986; *Leonov and Nikonov,* 1988; *Nesmeyanov and Barkhatov,* 1978; *Yablonskaya,* 1989].

The internal structure of the tectonic nappes, characterized by the complication of their frontal parts by the recumbent and overturned drag folds and of their back parts by extension-related dislocations (axial plane cleavage, boudinage, cutting veins, etc.), suggests the gravitational manner of their movements [*Ramberg,* 1988; *Rutten,* 1972]. At the same time the mechanism of the tear of the allochthonous masses from the basement and the driving force that moved the nappe rock masses from the places of their primary accumulation might have been of compression-type nongravitational nature.

The phase of the "main folding" controlled the principal morphological heterogeneity of the folding in the area of the fold system. Against the background of the general folding simplification from the axial to the peripheral regions the fields of comparatively intense folding deformation alternate sharply with the fields of less intense dislocation. The areas of most complex geometry are restricted to the cores of the anticlinoria and 1st- and 2nd-order anticlines, and also to the limbs of the synclinoria, whereas simpler forms are restricted to the cores of the synclinoria and large synclines. The linear fields of more and less complex dislocations replace one another in an en-echelon manner along their strikes. There are examples where the areas of extremely tense folded structure are surrounded on all sides by areas of significantly simpler folding. A gradual replacement of the holomorphic folding by an intermediate folding variety can be observed along and across the strike of the fold system as a whole or of some individual anticlinoria.

The specific morphology of the fold structure does not allow one to explain the folding formation during the "main phase" by the simple external compression of the mobile South Tien Shan mobile system from the side of the "rigid" Fergana-Kyzylkum and Afganistan-Tadjik rigid median masses surrounding it in the north and south. The source of deformation seems to have been located inside the mobile system itself, this being responsible for the extremely complex pattern of the distribution of the different folding types in plan. This source of deformation might have been the local compression of the sedimentary rocks along the basement strike-slip or overthrust faults [*Rogozhin,* 1993], or the

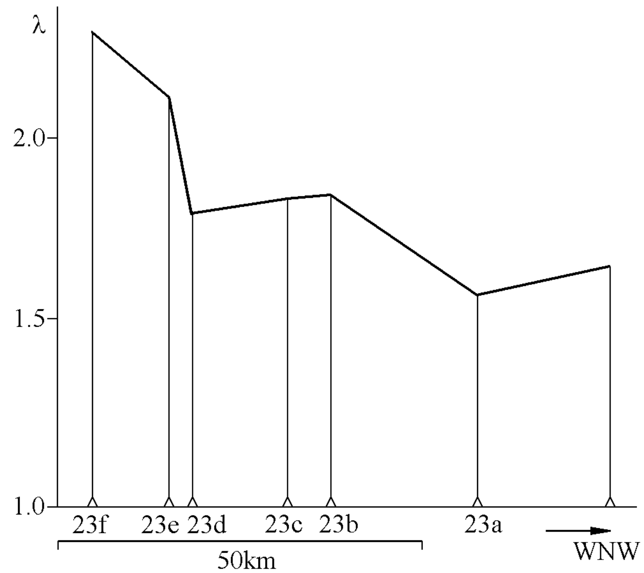

Figure 34. Variation of the redundant layer length λ for the rock sequences of the Zeravshan-Turkestan (Figure 16) in the direction of the pericline.

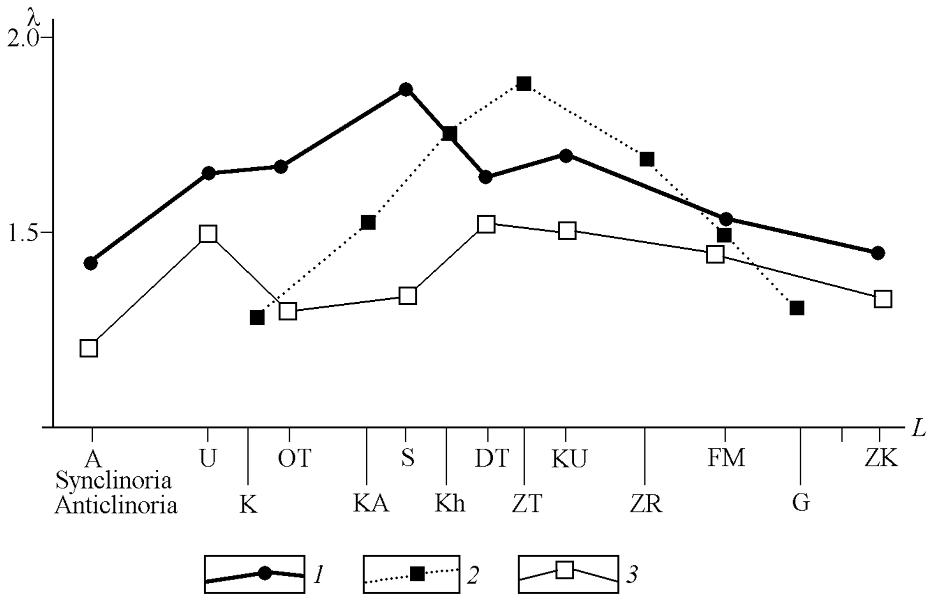

Figure 35. Curves showing the comparison of the coefficients of the redundant lengths of the layers λ for the geological sections of the anticlinoria and synclinoria transverse the strike of the South Tien Shan fold system (see Table 1 and 2). (1) for the synclinoria (overall Hercynian and Alpine deformation); (2) for the anticlinoria; (3) only for the Alpine synclinoria. The names of the fold structural features: synclinoria: (A) Aravan, (U) Uchkurgan, (OT) Okhna-Taldyk, (S) Surmetash, (DT) Daraut-Turkestan, (KU) Kshtut-Urmeta, (FM) Fan-Margib, (ZK) Zidda-Karakul; anticlinoria: (K) Kauzan, (KA) Kichikalai, (KH) Khodzhaachkan, (ZT) Zeravshan-Turkestan, (ZR) Zeravshan Range, (G) Gissar.

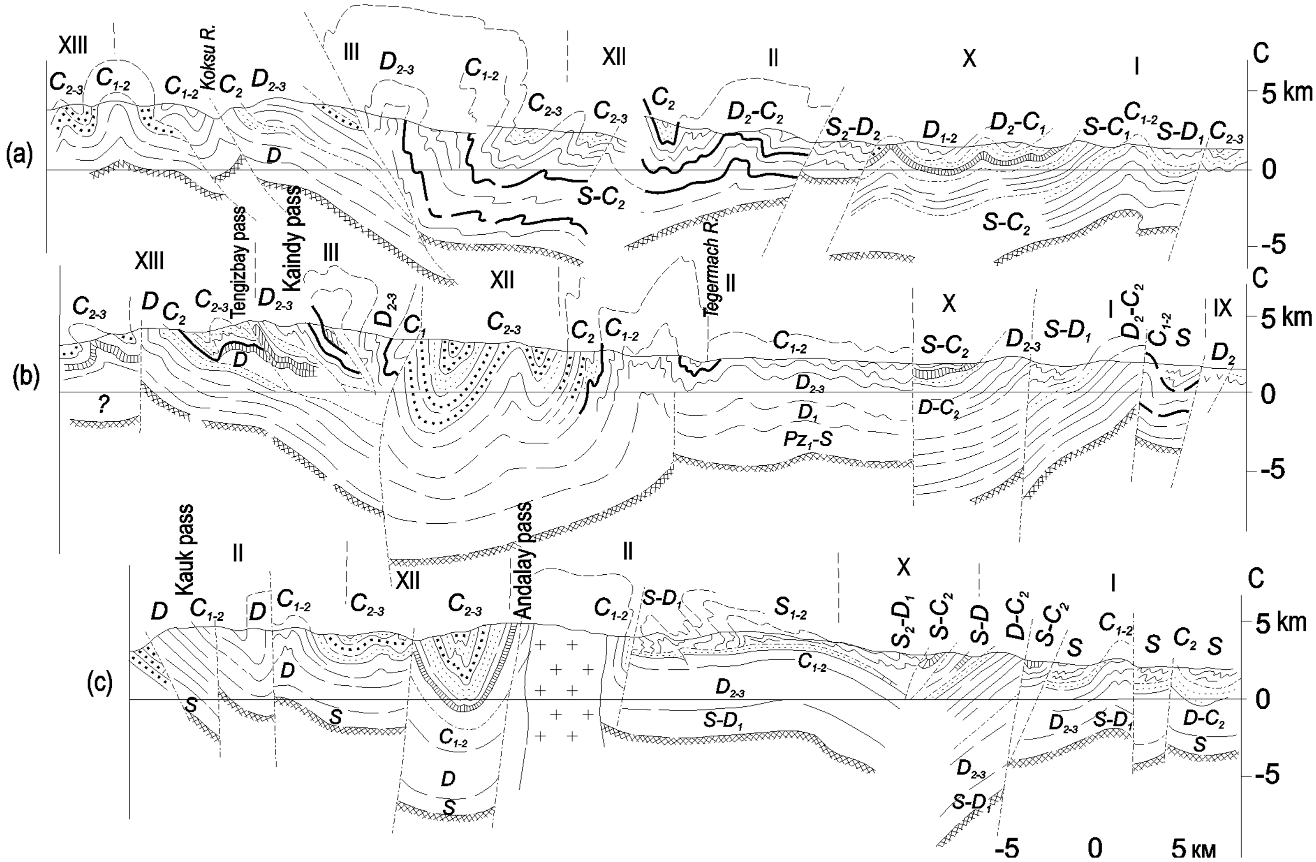

Figure 36. Generalized geological sections across the Alai Range: (a) at the meridian of the Shakhimardan and Aksu rivers, (b) at the meridian of the Isfairansai, Kainda, and Darautsai rivers, (c) at the meridian of the Abshirsai, Tegermach, Andalai, and Kayk rivers. See Figure 31 for the names of the large fold structures (Latin figures).

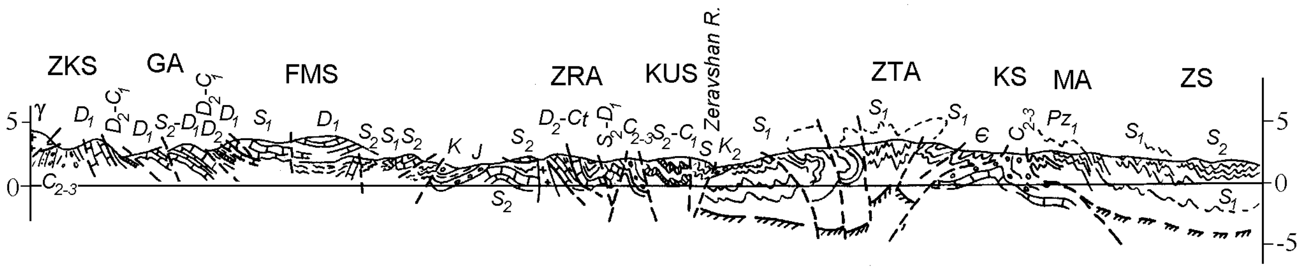

Figure 37. Generalized geological section along the meridian of the Altykol-Khushikat-Fan Dariya-Iskander Dariya-Kanchoch rivers. The names of the large anticlinoria: (GA) Gissar, (AZR) of Zeravshan Range, (ZTA) Zeravshan-Turkestan, (MA) Malguzar; the names of the synclinoria: (ZKS) Ziddy-Karakul, (FMS) Fan-Margib, (KUS) Kshtut-Urmetan, (KS) Kurganak, (Z) Zaama.

Figure 38. Photograph showing vertical, disharmonic folds in the sequence of Upper Silurian phyllite and marmorized limestone (Fan-Dariya R. Valley).

activity of diapir-type thick sedimentary rocks in response to the density inversion of the sedimentary and volcanic rocks. The fault-related compression, distributed in the mobile system might have provoked some diapiric or, rather advective, movements in the sedimentary cover of the mobile system [*Belousov,* 1975, 1985; *Ramberg,* 1988; *Sholpo et al.,* 1993]. The significant effects of the strike-slip displacements along the deep interzone faults in the axial parts of the fold system are proved by the widely developed phenomenon of en-echelon relations among the anticlinoria, synclinoria and individual large folds in the direction of their strikes.

The Alpine tectonic activity caused a significant effect on the formation of the fold structure of the South Tien Shan. During the recent geological history the fold system experienced not only the general block-dome rising, but also intensive lateral 20–50-percent compression which can be estimated from the dislocations of the Mesozoic-Cenozoic deposits in some synclinoria. Yet, similar to the "main folding" deformation, the greatest horizontal reduction is observed in its central axial zone, rather than in the marginal parts of the fold system (Table 2, Figure 35).

The geometrically different structural zones experienced different evolutions in the Paleozoic, Mesozoic, and Recent periods of time. The anticlinoria and broad divergent synclinoria experienced in the Middle Paleozoic the process of tectonic inversion and were involved in orogenic rising in the late Paleozoic. Their fold structure was shaped as a result of several folding phases, the early phases and the main Late Hercynian one. This is evidenced by their complex internal fold structure. An example is the southern limb of the Zeravshan-Turkestan, where the recumbent and overturned folds in the Lower Silurian rocks are disturbed by later superimposed folds with vertical axial surfaces (Figure 1i, and Figures 38 and 39). The northern limb of the Khodhaachkan shows the Lower Carboniferous intensely boudinaged limestone layers transformed to narrow folds overturned to the north (Structure III in Figures 13, 14, and 36). Finally, the Fan-Margib Synclinorium shows a wide development of superimposed folding in the metamorphic rocks of the Yagnobian Series [*Leonov,* 1985, 1990]

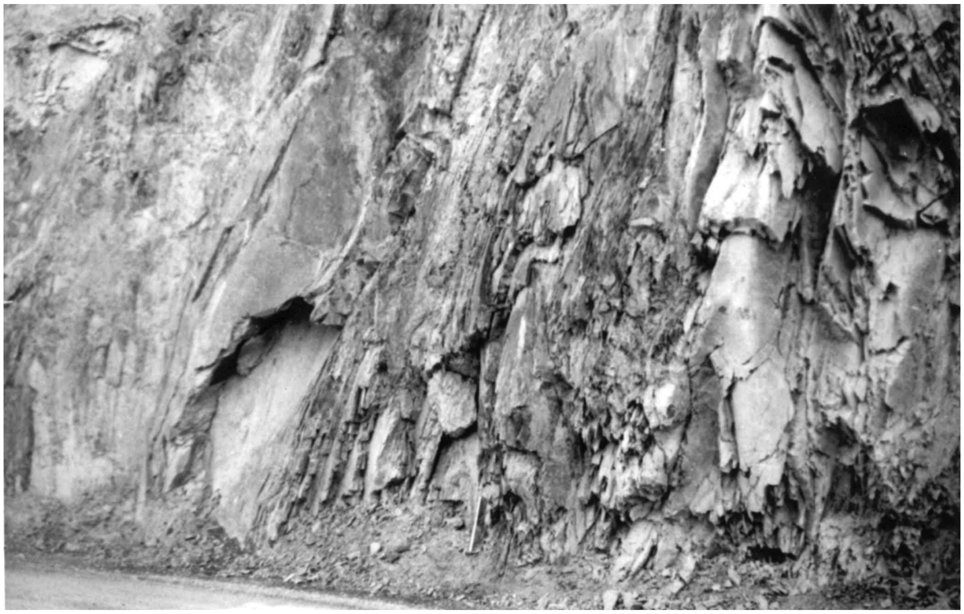

Figure 39. Photograph showing vertical, disharmonic, asymmetric folds with vertical hinges in a sequence of Devonian-Carboniferous phyllite and marmorized limestone (Fan-Dariya R. Valley).

and in the Lower Silurian quartzite (c and d in Figure 18; V in Figure 36). At the same time the narrow fault-related synvergent synclinoria had not experienced inversion. Folding there had been associated with the "main" Hercynian phase.

Conclusion

Disharmonic irregular holomorphic folding of the South Tien Shan, probably, appeared as a result of joint action of three reasons. The first factor is a deformation of sedimentary thickness and volcanic rocks in the process of gravitational moving of the nappe plates in the Middle Carboniferous epoch (before the main folding). The second one is an external horizontal shortening of the crystalline basement and the overlaying volcanic and sedimentary sequences. This factor, probably, dominate on the Alpine stage of evolutions of the fold system. The third factor is an advective motion in the complex of sedimentary cover. This factor reflects an internal gravitational powerful activity of sedimentary sequence with density inversion in the process of the main folding. Probably, the last phenomena has played an important role in folding morphology in Hercynian stage. At the same time the obvious association of the narrow extensive fields of intensive folding with the zones of large co-folding overthrust, thrust and strike-slip faults, separating the anticlinoria and narrow extensive synclinoria, suggests that the lateral shortening, caused by the local compression of the Hercynian rocks in the large fault zones affected the folding process in the Paleozoic Era, too.

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