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STRUCTURAL GEOLOGY OF VARISCAN TIEN SHAN, USSR

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ABSTRACT. Three epochs have been distinguished in the Variscan history of the Tien Shan geosynclinal system. The first epoch, geosynclinal downwarping, proceeded during the Silurian, Devonian, Lower Carboniferous, and, partly, Middle Carboniferous. The geosynclinal system of this time consisted of two continental blocks (northern and southern), separated by a eugeosynclinal basin of oceanic type; miogeosynclinal deposits accumulated on the continental blocks.

The second epoch, overthrusting, corresponds mostly to the Middle Carboniferous. As the continental blocks drew together, the oceanic basin closed, and appearance of a system of nappes appeared thrust over the southern continental block. The lower nappes consist of rocks from this southern block, whereas the upper sheets consist of rocks from the eugeosynclinal zone and the northern continental block. This epoch is characterized by the accumulation of flysch, wildflysch, and olistostrome deposits.

The third epoch, mountain building, embraces the Upper Carboniferous and Permian. At this time the nappes and autochthon were folded into a system of linear synforms and antiforms and were cut by reverse faults and thrusts. The folding was accompanied by the accumulation of terrigenous molasse-type deposits and acid volcanogenic rocks. The formation of granites is attributed to this epoch. At the end of this epoch one more stage of deformation produced strike-slip faults, folds with steep hinges, and horizontal flexures. This deformation continued into a later time when the region was under a platform regime.

The succession of deformations established for the Variscan orogenic cycle in the Tien Shan reflects a general tendency in the orogenic development of geosynclinal systems applicable to many linear folded belts, both Paleozoic and more recent.

INTRODUCTION

The Tien Shan is one of the largest mountain systems of Asia; its western part lies in the USSR. It consists of many mountain ranges; their watersheds are at heights of 4 to 5 km, and separate peaks rise considerably higher. The mountains are almost devoid of vegetation cover, and the rocks, mostly Paleozoic and older, are very well exposed. To the west, the Tien Shan ranges sink down toward the Turanian lowland, where the extension of their Paleozoic structures can be seen in low uplands among the deserts of Kyzyl-Kum.

The structure of the greater part of the Tien Shan was formed by Variscan movements. That part of the Tien Shan in the USSR is a middle link of the Ural-Tien Shan Variscan folded belt. The northern border of the Tien Shan Variscides lies against a zone of the Caledonian folding; the southern border against old platform massifs such as the Tarym "basin". Figure 1 shows the territory of the Variscan Tien Shan; it is divided into 10 geographic regions, the names of which are convenient for description.

The Variscan history of the geosynclinal system of Tien Shan can be divided into three epochs. The epoch of geosynclinal downwarping embraces the Silurian, Devonian, Lower Carboniferous, and partly the Middle Carboniferous. The overthrusting epoch corresponds mainly to the Middle Carboniferous. To this epoch belongs the first stage of Variscan deformation (F_1). The epoch of mountain building lasted through the

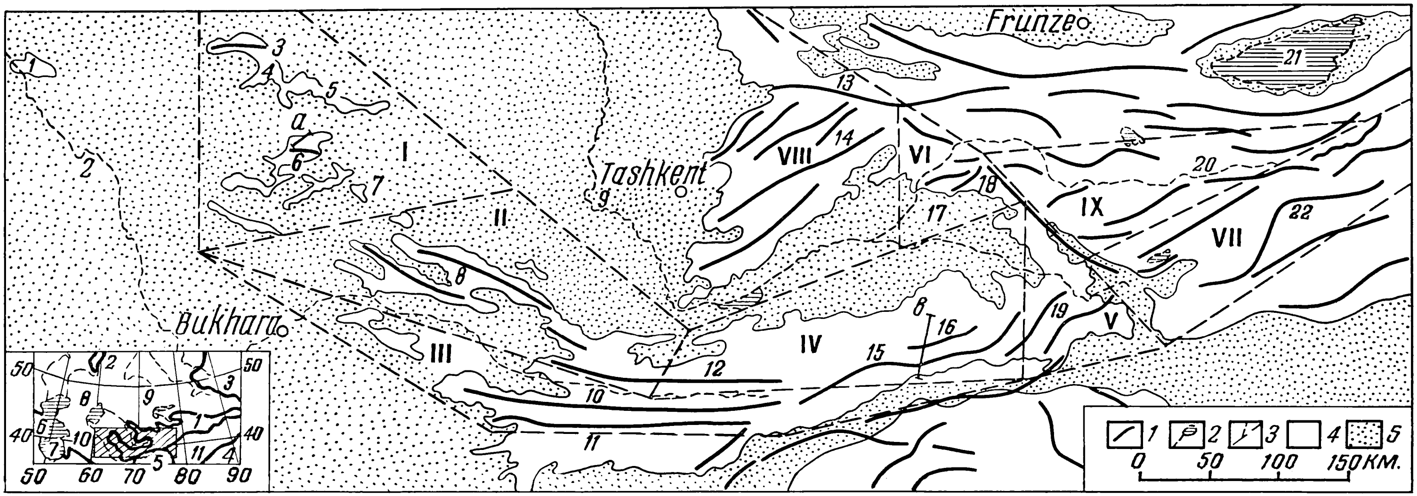


Fig. 1. Orographic map of the Tien Shan and vicinity:

(1) Mountain ranges; (2) rivers and lakes; (3) boundaries of geographical regions; (4) Paleozoic and pre-Paleozoic rocks; (5) Mesozoic and Cenozoic deposits.

I-IX. Geographical regions of the Variscan Tien-Shan: I. Kyzyl-Kum; II. Nurata; III. Gissar; IV. Alai; V. East Alai; VI. Baubashata; VII. Kokshaal; VIII. Chatkal; IX. Naryn.

The figures on the map mark: Alai range (15); Amu Darya river (2); Bukantau upland (3); Chatkal range (14); Dzhetymtau upland (5); Fergana basin (17); Fergana range (18); Gissar range (11); Issyk-Kul lake (21); Kichikalai range (16); Kokpatas upland (4); Kokshaal range (22); Naryn river (20); North Nuratau range (8); Sangruntau upland (7); Syr-Darya river (9); Sultanuizdag upland (1); Talass range (13); Tumdytau upland (6); Turkestan range (12); Zeravshan range (10).

On the small map: (1) to (6) mountain ranges: (1) Tien Shan, (2) Urals, (3) Altai, (4) Kuen-Lun, (5) Pamirs, (6) Caucasus; (7) Caspian Sea; (8) Aral Sea; (9) Kazakhstan; (10) Kara-Kum desert; (11) Tarym basin. The area of the larger figure is shaded.

Upper Carboniferous and Permian. This epoch is characterized by the second stage of deformation (F_2), whereas its end is marked by the third stage (F_3).

On stage F_1, nappes and recumbent folds were formed. In stage F_2, the nappes and autochthon were folded into vertical folds[1] and disturbed by faults and thrusts. In stage F_3, there appeared horizontal folds, wrench faults, and related thrusts and normal faults.

Historically, we see that the vertical folds and faults of stage F_2, the most common object of geological study, were described first of all. Some deformations of stage F_3 were also recognized long ago. As far back as 1919, D. V. Mushketov described a large horizontal flexure in the eastern part of the mountains surrounding the Fergana basin. In the thirties, V. N. Ognev (1939) and others pointed to the presence of wrench-fault dislocations along the fault stretching along the Talas and Fergana ranges. The deformations of stage F_1 were established considerably later. G. S. Porshnyakov described numerous thrusts in the mountains around the Fergana basin. According to Porshnyakov (1962, 1969; and other publications), these thrusts occurred in synclinal depressions. The thrusts in each synclinal depression were rooted there, and in cross section, the system of thrusts in each depression is fan-shaped. Thus, the thrust masses were each transported from the synclinal depressions out toward the neighboring anticlines, and, as a rule, such transport did not pass beyond the limits of one structure. In the process of further compression and folding of the synclinal depressions, the thrusts were also deformed.

The author of this paper (Burtman, 1968), arrived at the following conclusions: (1) the thrusts were not rooted, each in the nearest synclinal structure, but are parts of extensive nappes; (2) the synclinal structures and the anticlines are large synforms and antiforms that fold the nappes; (3) these large folds are later structures that appeared after the formation of the nappes.

The hypothesis presented in this paper about the structure of the Variscan Tien Shan and the history of its development is not the only viewpoint concerning the tectonics of this region. There are researchers who see in the Tien Shan neither nappes nor strike-slip faults, nor horizontal folds, and their ideas of the development of this folded system differ from those here presented (Sinitsyn, 1960; Rezvoi, 1959, 1972; Akhmedjanov, Borisov, and Fusailov, 1967; Akhmedjanov and others, 1972; Pyatkov and others, 1967; Kukhtikov, 1968).

TECTONIC UNITS FORMED BEFORE THE EPOCH OF MOUNTAIN BUILDING

Within the Variscan geosynclinal system, the following tectonic units can be distinguished by the rocks formed in each before the epoch of mountain building: (1) south miogeosynclinal; (2) south geoanticlinal;

[1] By a vertical fold, the author means a fold resulting from bending of the layers predominantly in the vertical direction. Bending of the layers predominantly in the horizontal direction forms either a horizontal fold (with a steep to vertical hinge) or a recumbent fold (with a gentle to horizontal hinge). The terms "synform" and "antiform" refer to vertical folds only.

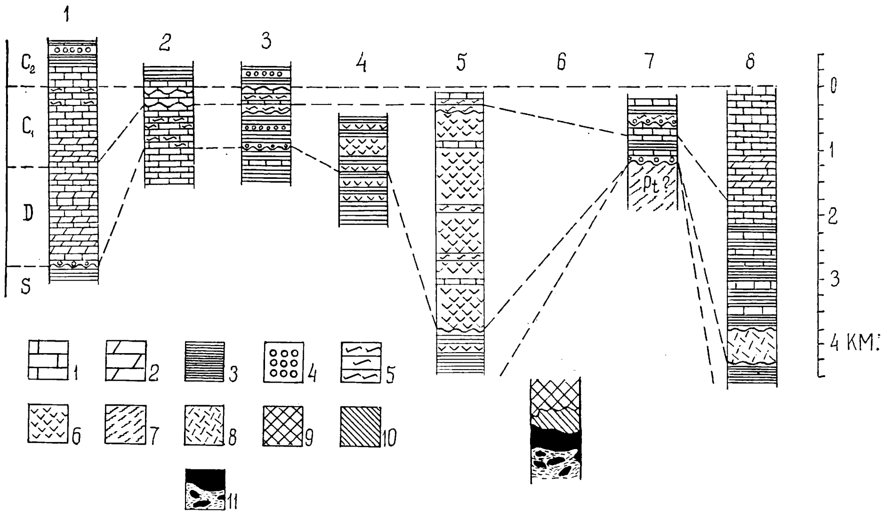


Fig. 2. Stratigraphic sections of the Variscan tectonic units of the Tien Shan: (1) south miogeosynclinal; (2) to (4) south geoanticlinal; (5) to (6) eugeosynclinal; (7) north geoanticlinal; (8) north miogeosynclinal. C_2—Middle Carboniferous, C_1—Lower Carboniferous, D—Devonian, S—Silurian, PT?—Proterozoic (?).

Signs in columns: (1) limestone; (2) dolomite; (3) fine-clastic and clay rock; (4) coarse-clastic rock; (5) siliceous rock (for example, chert); (6) basalt and andesite; (7) metamorphic green schist; (8) acid effusives; (9) gabbro; (10) pyroxenite; (11) serpentinized ultramafic rock and serpentinitic melange.

(3) eugeosynclinal; (4) north geoanticlinal; (5) north miogeosynclinal (fig. 2).

South miogeosynclinal unit.—The stratigraphic succession in rocks of this unit is the following (fig. 2, no. 1):

1. Silurian terrigenous deposits.
2. Carbonate deposits of the Devonian, Lower, and Middle Carboniferous[2], from 1000 to 2500 m. In the Baubashata and

[2] Correlation of the Carboniferous subdivisions used in the USSR, North America, and Western Europe.

USSR		North American		Western Europe
Upper Carboniferous		Virgilian Missourian	Pennsylvanian	Stephanian
Middle Carboniferous	Moskovian	Desmoinesian Atokan		Westphalian
	Bashkirian	Morrowan		
Lower Carboniferous	Namurian	////// ////// //		Namurian
		Chesterian	Mississippian	
	Visean	Meramecian		Visean
	Tournaisian	Osagian		
		Kinderhookian		Tournaisian

Kokshaal regions, among carbonate deposits in the Middle Devonian, lenses of volcanogenic rocks of andesite-basaltic composition (thickness up to 1000 m) are observed.

3. Middle Carboniferous flysch and olistostrome deposits — up to 500 m.

Stratigraphic contacts of Variscan miogeosynclinal deposits of the southern type with older rocks are known in the Kyzyl-Kum region where these deposits rest transgressively on Late Proterozoic rocks.

The above unit occurs autochthonously in most cases, that is, it forms the lowest structural unit known in the region. It may, however, be parautochthonous.

South geoanticlinal unit.—This unit is characterized by considerable gaps in the stratigraphic succession of Devonian and Lower Carboniferous rocks. Three subtypes can be distinguished within the south geoanticlinal unit: (a) carbonate, (b) carbonate-terrigenous, (c) volcanogenic-terrigenous.

The carbonate subtype of the south geoanticlinal unit (fig. 2, no. 2) differs from the miogeosynclinal type in being less complete stratigraphically and having a smaller thickness of Devonian and Lower Carboniferous deposits. Silurian limestones are frequent in this subtype.

The carbonate-terrigenous subtype consists of various facies complexes of deposits: (A) Silurian terrigenous deposits — from 1000 to 3000 m; (B) carbonate deposits of the Ludlow and Lower Devonian — from 0 to 1000 m; (C) Devonian graywackes — from 0 to 1000 m; (D) siliceous-slate deposits of the Devonian — from 0 to 500 m; (E) siliceous-carbonate and carbonate deposits of the Lower and Middle Carboniferous — from 0 to 500 m; (F) Middle Carboniferous flysch and olistostrome — from 0 to 1000 m. These facies complexes wedge out and replace one another from place to place over the region. Two or three such facies complexes (fig. 2, no. 3) are usually present in any given stratigraphic section. Frequently siliceous-carbonate deposits of the Lower and Middle Carboniferous rest directly on the Silurian terrigenous strata.

In the stratigraphic section of the volcanogenic-terrigenous subtype (fig. 2, no. 4) basalt and andesite effusives and tuffs are present. Units of volcanogenic rocks alternate with layers of terrigenous and carbonate rocks, but sedimentary rocks are generally predominant.

Eugeosynclinal unit.—Rocks of the oceanic basement (ultramafics, gabbro, amphibolite) and eugeosynclinal deposits forming the oceanic cover (Peive, 1969) can be distinguished in the eugeosynclinal unit.

The rocks of the oceanic basement (fig. 2, no. 6), as exposed in various parts of the region, have similar structures (Burtman and others, 1974). A good section can be observed in the Kyzyl-Kum region in the area of the Tumdytau upland, where the rocks form an allochthonous sheet. The following rocks take part in the structure from below upward:

1. Serpentinite melange with blocks of serpentinized peridotite, siliceous rock, and dolomite — 50 m.
2. Massive serpentinized ultramafics — 75 m.

3. Amphibolized pyroxenite — 150 m.
4. Metasomatic amphibolized gabbro — over 150 m.

The thickness of rocks composing the sections of the oceanic basement of the Variscides varies considerably. In the Sultanuizdag upland, amphibolized gabbro up to 2000 m and melanocratic amphibolites up to 1800 m, rest on the serpentine melange (its thickness being some hundred meters), all being allochthonous. The other allochthonous massif on the same upland is formed by a thick plate of peridotite, pyroxenite, and hornblendite.

Large massifs of ultramafics crop out in the piedmont at the northern slope of the Alai range. The Aravan massif (fig. 3, no. 18) is an allochthonous sheet 1 km thick. The lower part of this sheet is formed by a serpentinite melange (200 m); above it are serpentinized peridotite and pyroxenite. The Kan massif (fig. 3, no. 9) is formed by the serpentinite melange (pl. 1-A).

Variscan eugeosynclinal deposits have the following succession from below upward (fig. 2, no. 5):

1. Terrigenous, volcanogenic-terrigenous, siliceous-terrigenous, and carbonate-terrigenous Siluvian deposits — over 1000 m.

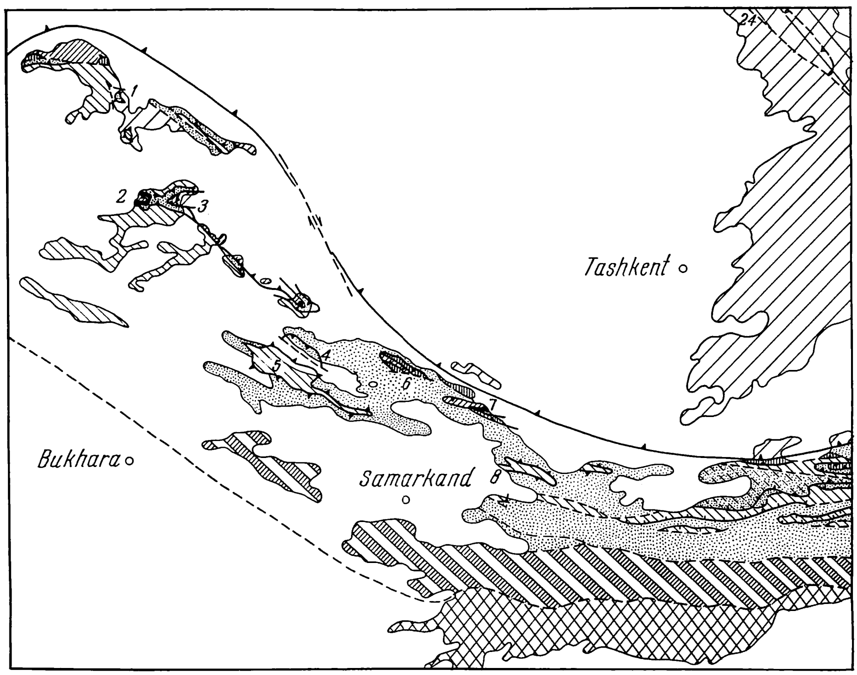


Fig. 3. Sketch of tectonic units (west, left page; east, right page).

(1) and (2) eugeosynclinal unit: (1) rocks of the oceanic basement (ultramafics, gabbro), (2) eugeosynclinal deposits; (3) north geoanticlinal unit; (4) to (6) south geoanticlinal unit: (4 volcanogenous-terrigenous subtype, (5) carbonate-terrigenous subtype, (6) carbonate subtype; (7) south miogeosynclinal unit; (8) structure not yet deciphered; eugeosynclinal and geoanticlinal deposits rest as allochthonous massifs on the rocks of

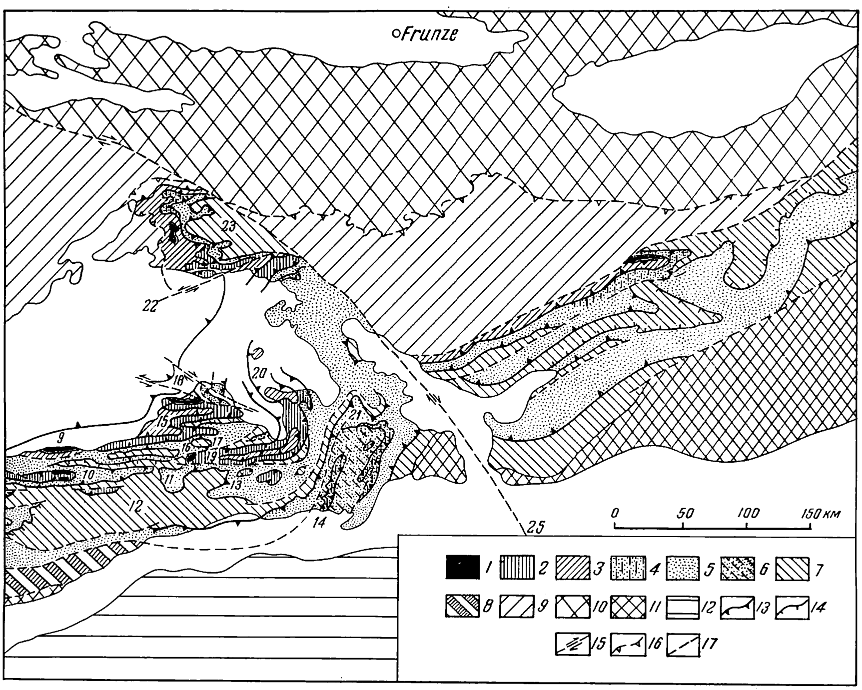
2. Volcanogenic deposits of spilite-diabasic and andesite-basaltic composition. These deposits are of Devonian and in some regions probably of Devonian to Lower Carboniferous age (thickness from 500 to 3000 m).

3. Siliceous, carbonate, and tuffogenic deposits of the Lower Carboniferous — up to 500 m.

The rocks of the oceanic basement and oceanic cover form various allochthonous sheets in most cases. On the northern slope of the Alai range (fig. 3, no. 10) gabbroids of the oceanic basement are overlain by non-metamorphosed Devonian volcanics.

North geoanticlinal unit (fig. 2, no. 7).—Geoanticlinad deposits of the northern type consist of terrigenous-carbonate, carbonate, and siliceous-carbonate sediments of the Devonian and Lower Carboniferous. The stratigraphic section of these deposits is characterized by gaps in sedimentation and an insignificant thickness of sediments, and they rest on metamorphic greenschists. The geoanticlinal complex forms allochthonous sheets; frequently in such sheets only the metamorphic rocks of the base of the unit are preserved.

North miogeosynclinal unit (fig. 2, no. 8).—The rocks of this unit are mostly autochthonous and occupy a considerable area (fig. 3). In the



the south miogeosynclinal unit; (9) north miogeosynclinal unit; (10) area of Caledonian folding; (11) platform massifs; (12) area of Alpine folding (Pamirs); (13)-(14) overthrust surfaces: (13) primary, (14) secondary; (15)-(17) faults of the F_3 stage: (15) wrench faults, (16) thrusts, (17) other faults.

Deposits and plutonic rocks of the epoch of mountain building are not plotted on the sketch.

north, near the border with the Caledonide zone, the Variscan miogeosynclinal basin inherited a more ancient molasse depression. In the stratigraphic section here, Lower Paleozoic eugeosynclinal deposits are overlain by molasse-type deposits of the Middle and Upper Devonian (over 1000 m) and these by carbonate deposits of the Upper Devonian and Lower Carboniferous (over 2000 m). Toward the south, within the Variscan geosynclinal system, the upper part of the molasse is replaced by carbonate-terrigenous deposits, under which appear Lower-Middle Devonian acid effusives and Silurian terrigenous deposits.

DEPOSITS OF THE OVERTHRUSTING EPOCH

The overthrusting epoch is a revolution in the geosynclinal history. The deposits of this epoch enable us to follow the development of the overthrusting process. Flysch and olistostrome deposits, synchronous with the formation of nappes, have been studied in the sections of the south miogeosynclinal and south geoanticlinal units but have not been unequivocally recognized in the eugeosynclinal unit. In the north geoanticlinal unit, such deposits have not yet been found.

South miogeosynclinal unit.—The flysch deposits of the Moscovian stage of the Middle Carboniferous everywhere crown the south miogeosynclinal stratigraphic succession. We managed to observe in some areas within the Kyzyl-kum, Alai, and East Alai regions that flysch deposits are replaced by wildflysch with blocks of rocks from the overlying allochthonous sheets. A good section is on the Tumdytau upland in the Kyzyl-Kum region, near the northern foot of the Muruntau mountains (fig. 3, no. 2). Under the floor of the allochthonous sheet (fig. 4, no. 1), composed of Silurian (Wenlockian) flinty-quartzy puddingstone, gritstone, and sandstone, there occur from above downward:

1. Moscovian wildflysch. The matrix is formed by flysch consisting of calcareous sandstone, siltstone, and argillite. Olistolites are formed by the following rocks: (A) flinty-quartzy gritstones, puddingstones, and sandstones transported from the frontal part and from the foot of the overlying allochthonous sheet — such olistolites are rounded and sized from 10 to 100 cm; (B) Lower Devonian limestone sliding into the sediment from higher in the stack of allochthonous sheets — some olistolites are round, some are lenticular (squeezed) boudins formed at the expense of flat olistolites. The largest "lens" of Devonian limestone in the Carboniferous flysch is 20 m long and 6 m thick. The wildflysch is up to 50 m thick.
2. Moscovian flysch — 200 m.
3. Limestone, the upper part of which belongs to the Lower Moscovian substage and the lower part to the Lower Devonian — 2500 m.

Flysch and olistostrome deposits were strongly tectonized when the stack of nappes overrode them (pl. 2).

PLATE 1

A.

B.

A. Serpentinite melange in the Kan massif, Alai range (fig. 3, no. 9). Lumps are composed of massive serpentinized ultramafics; the matrix is serpentinite penetrated by carbonate veins. B. Tectonized olistostrome in the third allochthonous sheet, Tumdytau upland (fig. 4). Eugeosynclinal unit, Middle Paleozoic. Lumps are composed of sandstone, chert, and dolomite of Upper Proterozoic and Cambrian age. The matrix is silty slate.

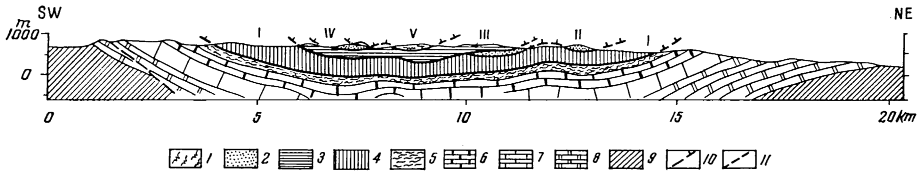


Fig. 4. Geological section through the northern part of the Tumdytau upland along line "a" in figure 1.

(1) to (4) allochthon: (1) metamorphic green slate, Proterozoic (?); (2) ultramafic and gabbroid rocks; (3) Middle Paleozoic olistotrome; (4) Silurian terrigenous rocks; (5)-(6) autochton; (5)-(6) Middle Carboniferous (5. flysch and olistostrome, 6. limestone); (7) Lower Carboniferous limestone and dolomite; (8) Devonian limestone and dolomite; (9) Proterozoic; (10) overthrust surfaces; (11) later faults.

South geoanticlinal unit.—Flysch deposits of the overthrusting epoch are known in most of the sections of this unit. Olistostrome deposits have been found in the Kyzyl-Kum, Nurata, Gissar, Alai, and East Alai regions, mostly evident in the Kyzyl-Kum and Nurata regions. In these regions the deposits concerned are located in the Bukantau, Dzhetymtau, and Sangruntau uplands and in the North Nurata range. The strata are strongly tectonized and some hundred meters thick. The matrix of the strata is formed by clayey and flinty slate alternating with sandstone; a Middle Carboniferous fauna was found in the sandstones. In the matrix there are separate blocks consisting of: (A) sandstone, (B) chert, (C) basic volcanogenic rock, (D) metamorphic greenschist, (E) limestone with faunas of the Upper Silurian, the Lower Devonian, the Lower Carboniferous, and the Bashkirian stage of the Middle Carboniferous. Most of the blocks of sedimentary rock are authigenic, rolled boudins of rocks from the south geoanticlinal unit. The effusive rocks can belong either to the south geoanticlinal unit or to the overlying eugeosynclinal unit. The blocks of metamorphic schists are olistolites supplied from the upper allochthonous sheet.

Eugeosynclinal unit.—In the Tumdytau upland a thick olistostrome stratum forms an allochthonous sheet (fig. 4, no. 3), occupying the same structural position in the section of the Tumdytau upland as the allochthonous sheet formed by the rocks of the oceanic cover of the eugeosyncline in other areas. This fact, as well as the composition of blocks in the olistosome, enables us to suggest that the given stratum belongs to the eugeosynclinal complex. The stratum is composed of clay slate with interlayers of sandstone and blocks of dolomite with a Cambrian fauna, basic effusives, gabbroid rocks, serpentinized ultramafics, and plagiogranites (pl. 1-B). Some blocks are measured in tens and hundreds of meters. Boudins of sandstone are frequently turned over, sometimes they are folded. The blocks are often compressed.

An analysis of the deposits of the overthrusting epoch shows that the overthrusting process was taking place in submarine conditions. Allochthonous sheets were moving along on previously undeformed and unconsolidated sediments.

STRUCTURAL POSITION OF TECTONIC UNITS AND F_1, F_2 DEFORMATION STUDIES

The tectonic succession of the above units in the normal geological section throughout the Variscan Tien Shan is the following (from below upward):

1. south miogeosynclinal unit;
2. south geoanticlinal unit;
3. eugeosynclinal unit;
4. north geoanticlinal unit;
5. north miogeosynclinal unit.

All these units are separated from one another by thrust surfaces. Each unit can consist of one or several allochthonous sheets. The lower parts of sheets are frequently composed of Silurian rocks, and the upper parts of Carboniferous rocks. In geological sections one can observe Carboniferous rocks that are conformably or almost conformably overlain by Silurian rocks.

The overthrust surfaces presented on the map (fig. 3) are divided into primary and secondary. A primary overthrust surface is a surface on which the rocks of one tectonic zone (as marked out in the epoch of geosynclinal downwarping) were thrust over the rocks of a neighboring zone. The secondary overthrust surfaces appeared during the movement of nappes. They frequently cut the already formed stacks of sheets. On these secondary overthrust surfaces, any tectonic units can be contiguous with one another, and the geological sections can be doubled. The overthrust surfaces were considered of primary or secondary type on the basis of: (A) an analysis of the facies of the deposits separated by the overthrust surface; (B) correlation of successions of allochthonous units in geological sections of various regions; (C) study of structural relationships of the overthrust surface to the bedding of the overlying and underlying rocks: the primary overthrust surfaces are conformable whereas the secondary ones usually cut across the bedding.

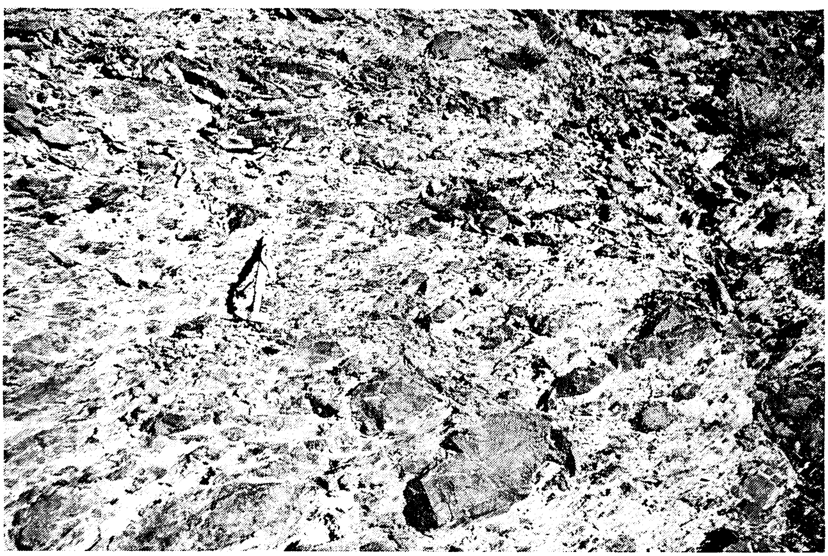
The nappes produced in the F_1 stage, as observed now, have been deformed by later dislocations of the F_2 and F_3 stages. The deformations of the F_2 stage occurred throughout the Variscan geosynclinal system, whereas the deformations of the F_3 stages are concentrated in certain areas. We give first a description by regions of the F_1 nappe structure and the result of its deformation in the F_2 stage. Dislocations of the F_3 stage are described below.

Kyzyl-Kum region.—The rocks of the south miogeosynclinal unit are distributed over vast areas of the Kyzyl-Kum region where they are autochthonous. The other tectonic units occur as tectonic outliers of different size. The overthrust structure of the region is most clearly reflected in the Tumdytau upland, as the territory of this upland was only slightly affected by deformation of the F_2 stage. The northern part of this upland is a gentle synform (fig. 3, no. 2), on both limbs of which autochthonous rocks are exposed; in the core of the fold lie the allochthonous sheets (fig. 4). The lower allochthonous sheet (I) consists of rocks of the south geoanticlinal unit, here attributed to the carbonate-terrigenous

PLATE 2

A.

C.



Deposits of the overthrust epoch. South miogeosynclinal unit. Moscovian stage. The deposits lie beneath the first allochthonous sheet on the Tumdytau upland in the northern part of the geological section presented in figure 4.

A. Tectonized wildflysch (olistostrome) 25 m below the base of the first allochthonous sheet. The lumps are Wenlockian gritstone and sandstone from the overlying allochthonous sheet.

PLATE 2

B.

D.

B, C, and D. Tectonized flysch. In (B) 50 m below the overthrust surface the strata are completely disturbed, and boudins of sandstones are overturned, rolled, and tight. In (C) 80 m below the overthrust surface rolled and tight boudins are mixed with elongated boudins with sharp angles at the ends. In (D) 125 m below the overthrust surface the thicker sandstone beds can be traced over a considerable area with only incipient boudinage; the thinner intercalations are crushed.

sub-type. Sheets II, III, and IV are composed of rocks of the eugeosynclinal unit. Volcanogenic rocks of the oceanic cover are widely developed on the Bukantau upland, where they were overthrust onto the south geoanticlinal unit. In Tumdytau a similar structural position is taken by allochthonous sheet III, formed by an olistostrome stratum, which thus appears to belong to the oceanic cover of the eugeosynclineal unit. Sheets II and IV consist of rocks of the oceanic basement, that is, ultramafic and gabbroid rocks. The allochthonous sheets composed of Proterozoic(?) metamorphic slates (fig. 4, no. 5) and of Late Proterozoic-Cambrian eugeosynclinal deposits (fig. 3, no. 3) occupy the highest position in the cross section of the region. The metamorphic schists similar to those of sheet V are also exposed in the mountains around the Fergana basin, where they serve as a base for the north geoanticlinal section of the Variscides. Late Proterozoic-Cambrian eugeosynclinal deposits similar to those in the allochthon of the Kyzyl-Kum region occur at the base of the north miogeosynclinal Variscan section.

In Tumdytau and in the Kokpatas window (fig. 3, no. 1), one can see gentle overthrust surfaces. In the rest of the Kyzyl-Kum region the overthrust surfaces and allochthonous sheets dip steeply; in the northern part of the Bukantau upland they are locally overturned northward.

Nurata region.—Here the rocks of the south miogeosynclinal unit are exposed in the windows Debelyand (fig. 3, no. 5), Malguzar (fig. 3, no. 8), and in smaller windows in the eastern part of the region. The windows are in the cores of antiforms; the Debelyand window measures 120 by 15 km; the Malguzar window, 45 by 9 km.

Silurian and still older deposits occupy the greater part of the Nurata region. They are stratigraphically overlain by Devonian and Lower Carboniferous deposits of the south geoanticlinal type. These deposits are attributed to the carbonate-terrigenous subtype. The Nurata region is also characterized by geoanticlinal deposits of the carbonate subtype. They rest, as tectonic outliers (fig. 3, no. 4), on geoanticlinal deposits of the carbonate terrigenous subtype. The tectonic floor of the south geoanticlinal unit is exposed on the limbs of antiform folds. In the western part of the Debelyand window (fig. 3, no. 5), this tectonic surface dips 30° to 50°; in the eastern part of the window it dips even more steeply, being locally overturned. The rocks of the eugeosynclinal unit occupy a higher structural position in the cross section of the Nurata region. These rocks occur in the allochthonous massifs (fig. 3, nos. 6, 7) in the cores of synform folds. The folds are closed, almost isoclinal, locally overturned northward.

In the northeastern part of the Nurata region, rocks of the north miogeosynclinal unit crop out, forming isolated uplands.

Alai region.—In the Alai region there are some large vertical folds. In the cores of the large antiforms the rocks of the south miogeosynclinal unit are exposed. The largest antiform is the Kichikalai fold. In its core the rocks of the south miogeosynclinal unit occupy a vast territory (fig. 3, no. 12) along the watershed of the Alai and Kichikalai ranges. This antiform is a complicated structure. On the whole, its southern limb is steeper than the northern one. Allochthonous sheets composed of the rocks of the south geoanticlinal unit form its limbs, and in the eastern part of the Alai region these sheets are still preserved near its axial part. The Tegermach allochthonous massif formed by the rocks of the south geoanticlinal unit is perhaps the clearest (fig. 3, no. 11; fig. 5). In small tectonic windows within this massif one can see how Silurian rocks of the allochthon overlie Middle Carboniferous strata. Thrust surfaces in these windows are almost horizontal. The gentle dip of the base of the nappe (10-20°) is also observable near the eastern and western margins of this allochthonous massif. The Tegermach allochthon massif is not entirely isolated; the thrust surface beneath it continues to the east, along the margin of the Gezart half-window. Near the northern margin of this half-window the thrust surface is inclined from 40° to 60°; along the southern and eastern margins it is steeper.

A chain of antiforms underlies the northern part of the Alai range. The rocks of the south miogeosynclinal unit are exposed in the cores of the antiforms in tectonic windows; the largest is the Arpalyk window (fig. 3, no. 16), 60 by 7 km. This antiform is inclined and partly overturned northward, so that the overthrust surface along the northern margin is steep and locally overturned. The dip of the surface near the southern margin of the window is from 10° to 60°.

The south miogeosynclinal unit also forms allochthonous sheets limited by secondary overthrusting planes and horsts bordered by more recent faults.

The rocks of the Variscan eugeosynclinal unit and also metamorphic greenschist occur in the cores of the large synforms. The large synform Kirgazata (figs. 3 and 6, no. 19) is asymmetrical, the southern limb being steeper than the northern. The overthrust surface at the base of the eugeosynclinal unit on the northern limb of this fold dips 50° to 60°, flattening out locally to 20°. On the southern limb the surface is inclined at 70° to 80°. The Kirgizata fold is a link in the chain of synforms that

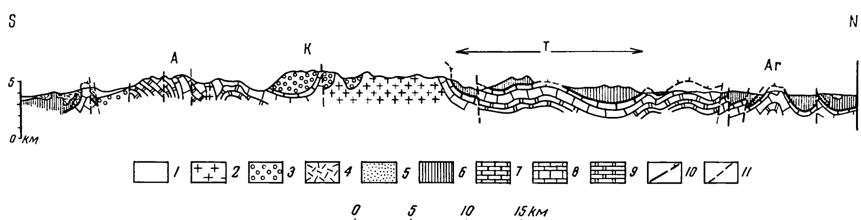


Fig. 5. Geological section through the Alai and Kichikalai ranges along the line "b" in figure 1.

(1) Mesozoic and Cenozoic; (2) Permian granites; (3 Upper Paleozoic molasse; (4)-(6) allochthon: (4) Carboniferous chert and limestone, (5) Devonian terrigenous rocks, (6) Silurian terrigenous rocks; (7)-(9) Autochthon; (7) Middle Carboniferous olistostrome, flysch, and limestone; (8) Lower Carboniferous limestone; (9) Devonian limestone and dolomite; (10) overthrust surfaces; (11) Later faults.

A—Alai range, K—Kichikalai range, T—Tegermach outlier (no. 11 in fig. 3), Ar—Arpalyk window (no. 16, fig. 3).

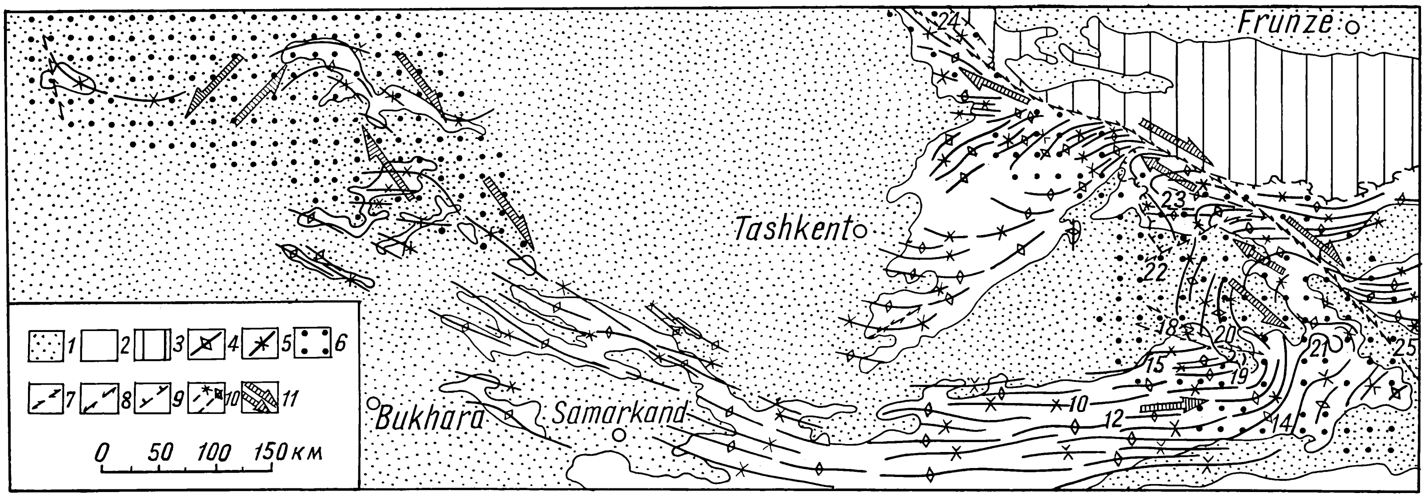


Fig. 6. Structural forms of the F_2 and F_3 stages.

(1) Mesozoic and Cenozoic; (2)-(3) Paleozoic and pre-Paleozoic: (2) Variscides; (3) Caledonides; (4)-(5) structures of the F_2 stage: (4) anticlinal and antiformal folds; (5) synclinal and synformal folds; (6)-(10) structures of the F_3 stage: (6) zones in which dislocations of the F_3 stage were most intense (Fergana and Kyzyl-Kum); (7) left-handed strike-slip faults; (8) right-handed strike-slip faults; (9) thrusts; (10) vertical folds in the Baubashata block; (11) directions of relative migration of masses at the F_3 stage.

can be traced toward the west to the Kyzyl-Kum region. In the Alai region there is one more link of this chain — the Okhna synform (figs. 3 and 6, no. 10).

In the northern part of the Alai region is the large complicated Karachatyr synform (figs. 3 and 6, no. 15); on its limbs all the tectonic units are exposed except the north miogeosynclinal unit.

Gissar region.—The south miogeosynclinal unit of this region is autochthonous. Allochthonous sheets consist of rocks of the south geoanticlinal unit, metamorphic greenschist, and, perhaps, eugeosynclinal deposits. The structure of this region has not been well enough studied, and the allochton units have not yet been mapped. Toward the east, the Variscan structures of the Gissar region plunge under Mesozoic and Cenozoic deposits and under the Pamirs, which were overthrust toward the north in Alpine time, but they reappear at the Earth's surface in the East Alai region.

East Alai region.—This region is composed of rocks of the south miogeosynclinal unit (autochthon) and of allochthonous sheets formed of the rocks of the south geoanticlinal unit. On the whole, this region has a synformal structure (fig. 3, no. 14); the south miogeosynclinal unit appearing on both limbs of this large F_2 synform. The inclination of the roof of the autochthon is mostly steep; only in some places in the western part of the region can one observe a gentle dip of this overthrust surface on the arches of small antiforms.

The south geoanticlinal unit forms several allochthonous sheets; the deposits forming these sheets belong to the various subtypes of the geoanticlinal section. The succession of the main sheets from below upward is as follows:

1. Sheet of rocks of the carbonate-terrigenous subtype.
2. Sheet of rocks of the volcanogenic-terrigenous subtype.
3. Sheet of rocks of the carbonate subtype.
4. Sheet of rocks of the volcanogenic-terrigenous subtype. This sheet rests in the core of the synform (figs. 3 and 6, no. 14).

Baubashata region.—In the Baubashata region there are some vertical folds. (fig. 6). The rocks of the south miogeocynclinal unit (fig. 3, no. 23) are exposed on the surface over a considerable area in the eastern part of the Baubashata region and are overlain by the rocks of the south geoanticlinal unit. The overthrust surface separating these tectonic units is mostly inclined at 40° to 60°, sometimes at 20° to 30°. Higher up are allochthonous sheets formed by the eugeosynclinal and north geoanticlinal units. In the northern part of the Baubashata region the north geoanticlinal unit is overridden by the north miogeosynclinal unit.

The Kokshaal region has been less well studied. The general succession of allochthonous sheets composed of various tectonic units seems to be just the same as described for the area west of the Fergana range.

The Chatkal and Naryn regions consist entirely of rocks of the north miogeosynclinal unit. It lies in contact with other Variscan tectonic units along young faults, or the contacts are buried by recent deposits. Only in certain places can we find evidence on the tectonic position of the north miogeosynclinal unit. One such place is in the northern part of the Baubashata region, where rocks of the north miogeosynclinal unit are thrust over rocks of the north geoanticlinal unit.

Deformations of the F_1 stage have not been found in the Chatkal and Naryn regions, whereas vertical folds and faults of the F_2 stage are widely distributed in both regions (fig. 6).

DIRECTION OF OVERTHRUSTING AND SEQUENCE OF MOVEMENT OF THE SHEETS

By direction of overthrusting is meant the direction of movement of an allochthonous sheet relative to an underlying sheet or to the autochthon. In this definition we do not take into consideration which of the elements concerned was active and which passive. To solve the problem of the direction of overthrusting in the Alai area, a study of folded structures of the F_1 stage was carried out, as well as an analysis of the facies of the Devonian deposits in various tectonic units (Burtman and Shmidt, 1970; Burtman and Klishevich, 1971).

The vergence of folds of the F_1 stage was analyzed in rocks of the south geonanticlinal unit forming the Tagermach tectonic outlier (fig. 3, no. 11; fig. 5). This tectonic outlier has dimensions of 20 by 20 km. It is composed of Silurian sandstone and shale, 1.5 km thick. The Silurian rocks rest on Middle Carboniferous deposits which belong to the south miogeosynclinal unit. The Tagermach tectonic outlier was relatively little affected by deformations of the F_2 stage; this made us choose it as an object of study. The bedding of the autochon, that of the allochthon, and the overthrust surface are on the whole parallel. Isoclinal and closed folds, as well as S-shaped flexures, are widely developed in the allochthon. Each such flexure consists of two conjugate closed folds: synclinal and anticlinal.

Two hundred twenty closed and 60 isoclinal folds have been described in the Tagermach tectonic outlier. Among them 105 folds have an amplitude from 0.5 to 10 m, 162 folds from 10 to 100 m, and 13 folds over 100 m. In all the folds described, the top and bottom of the beds have been determined; this prevented confusion of synclinal structures with inverted anticlines. The main methods for establishing top and bottom of beds were graded bedding, cross bedding, and scour features.

The axial surfaces of isoclinal folds and the long limbs of compressed flexures are parallel to the dip of an allochtonous sheet at a given place and parallel to the inclination of the overthrust surface. These folds have been attributed to the F_1 stage according to the following observations: (1) the system of folds has one vergence in all parts of the outlier; (2) the vergence of the above folds is directed in the same direction on both slopes of the large vertical fold of the F_2 stage; (3) recumbent isoclinal folds were observed in the axial parts of large folds of the F_2 stage. It was also assumed that the direction of overturning in folds formed in an allochthone during the movement of a nappe indicates the direction of relative displacement of the allochthon. Polar equal-area projections of the intersections with the surface of the upper hemisphere of lines lying in the axial plane perpendicular to the fold axis are presented in figure 7. Diagram A reflects the recent orientation of folds of the F_1 stage. It shows the total effect of two stages of deformation: F_1 and F_2. For the purpose of study it is desirable to take away the effect of the second stage of deformation. This was achieved by introducing a correction determined for each outcrop or group of neighboring outcrops. The value of the correction was estimated by considering that at the F_1 stage the isoclinal folds were recumbent folds with horizontal or almost horizontal axial surfaces. Diagram B is compiled after these corrections. On the basis of this diagram the following conclusions can be drawn: (1) the movement of the allochthonous sheet relative to the autochthon was toward the south; (2) the axial surfaces of closed (but not isoclinal) folds in the allochthon originally had an inclination mostly between 10° and 35°.

The data obtained through studying the folded structures of the Tegermach tectonic outlier are in good accordance with the observations of vergence of folds of the F_1 stage carried out in other parts of the Alai region and in Kyzyl-Kum.

Further evidence that the sheets moved southward was obtained by analysis of the depositional facies in these sheets. Let us refer to the rocks of the eugeosynclinal unit distributed in the eastern part of the Alai region. In the northwestern part of this area the Devonian eugeosynclinal deposits are mostly lavas, but to the southeast, besides the lavas, tuffs and cherts in the Devonian are widely developed. In the East Alai region the allochthonous sheet consisting of rocks of the volcanogenic-terrigenous sub-type of the south geoanticlinal unit occupies a structural position

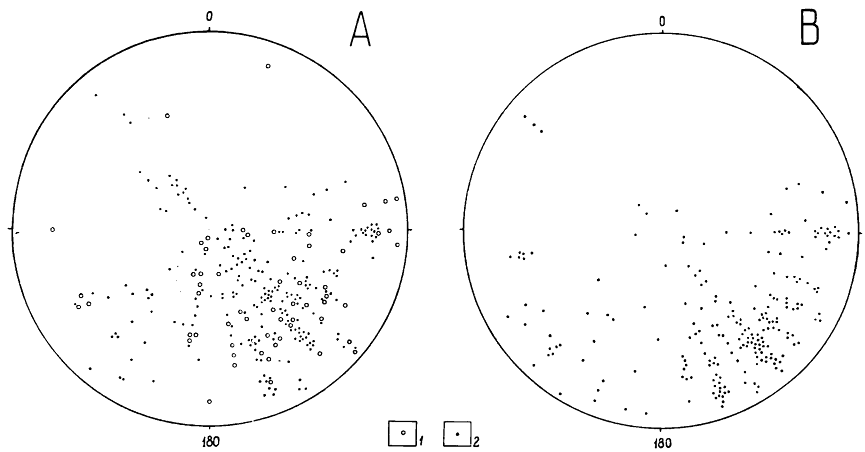


Fig. 7. Diagrams of vergence of folds in the Tegermach outlier.
A—inclination of axial surfaces of F_1 folds in the present system of coordinates. B—reconstruction of the position of axial surfaces of F_1 folds before F_2 deformation. 1—isoclinal folds (presented on diagram A only); 2—closed folds.

similar to that of the eugeosynclinal unit in the Alai region, and it is very likely to be a part of the same nappe. Terrigenous rocks prevail in this sheet in the Devonian deposits, whereas basic lavas and tuffs form separate interlayers only. In this case the eugeosynclinal features become more pronounced in a northwestern direction. In the Kyzyl-Kum region, the eugeosynclinal features of the south geoanticlinal unit are intensified in the north and northeast direction (Burtman, 1973).

The formation of the nappe system was over by the Upper Moscovian in the greater part of the territory, for Late Moscovian deposits rest transgressively on all allochthonous sheets and on the authchthon. A study of deposits directly underlying the allochthonous sheets showed that more recent rocks underlie the lower sheets, whereas older rocks underlie the upper sheets. These data enabled G. S. Porshnykov to conclude that the formation of upper nappes took place earlier than that of the lower nappes, and this conclusion appears to be correct for the beginning of the nappe movements. Thus the lower age boundary of the deposits of the overthrusting epoch in the various tectonic units lies in the interval between the Namurian and the Lower Moscovian; such sedimentation began in the Namuzian or Bashkirian in the eugeosynclinal unit, but in the south geoanticlinal unit, now in a lower structural position, it began in the Moscovian.

Worth attention are the data obtained in the Alai region on the age of deposits of the overthrusting epoch in the south miogeosynclinal unit. Deposition of the terrigenous flysch in the northern part of this region began at the beginning of the Moscovian stage, whereas in more southern areas it began somewhat later, in the middle of the Moscovian.

When the stacked-up sheets had already begun, movement of individual members of the stack proceeded at different rates. As a result, the original succession of nappes was interrupted, as shown by the relationships between the sheets observed in some areas. Let us turn, for instance, to the relation of the eugeosynclinal unit to underlying tectonic units as observed on the northern slope of the Alai range. In the foothills, the eugeosynclinal unit is thrust over the southern geoanticlinal unit, but farther south it overlies a lower structural unit formed by the rocks of the south miogeosynclinal unit (fig. 3, no. 19). Still farther to the south the eugeosynclinal unit rests on the south geoanticlinal unit (fig. 3, no. 13). Such relationships show that under the sheet of the eugeosynclinal unit there is a window in the underlying sheet, the one composed of rocks of the south geoanticlinal unit. Such buried windows are also known in other areas of the Alai, Kyzyl-Kum, and Baubashata regions. These windows could be produced either by the rupture of a sheet during differential movement of sheets in the stack or by overlapping an already formed tectonic window.

Other cases of disturbance of the original succession of sheets are the result of the secondary thrust surfaces formed in later stages of the thrusting, as already mentioned.

PRIMARY TECTONIC ZONATION OF THE VARISCAN GEOSYNCLINAL SYSTEM

A reconstruction of the primary tectonic zonation that existed before the overthrusting epoch is presented as a palinspastic profile (fig. 8), on which the succession and approximate width of the primary zones are shown. This reconstruction is based on the above conclusions concerning the succession and direction of movement of the sheets. Taken as a whole, the primary structure of the Variscan geosynclinal system of the Tien Shan is interpreted as two continental blocks (fig. 8, a-d, g-i), divided by a eugeosynclinal structure which had an oceanic crust (fig. 8, e-f). The original width of the oceanic structure is not known. At or near the margin of the platform massif (fig. 8, a) another oceanic structure of rift type seems to have existed in Carboniferous time. The basic effusives and ultramafic rocks distributed near the southern boundary of the Gissar region (Vlasov and Tarasenko, 1970) speak in favor of such an assumption.

The total shortening of the Variscan geosynclinal system of the Tien Shan during the overthrusting epoch can be estimated (even without considering a change in the width of fig. 8, zone f) at from 150 to 300 km in various regions. The amplitude of overthrusting of individual tectonic units was mostly less than 100 km.

SEDIMENTARY AND MAGMATIC ROCKS OF THE MOUNTAIN-BUILDING EPOCH

Sedimentation related to the formation of dissected topography began in the rear parts of overthrusting tectonic units as far back as the time of thrusting. Later on, such sedimentation continued against the background of folded structures of the F_2 stage. The mountain-building movements were manifested over vast areas, including the Caledonian belt.

In the southern part of the Chatkal region in the Carboniferous, Permian, and Early Triassic a thick sequence of continental volcanogenic rocks accumulated, mostly of acid composition. Similar volcanics

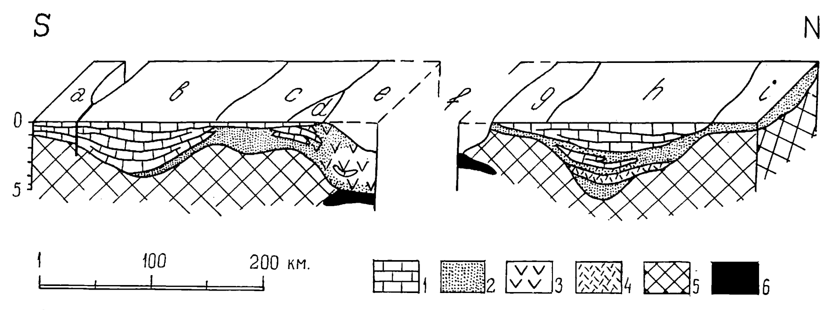


Fig. 8. Primary tectonic zonation of the Variscan geosynclinal system of the Tien Shan.

(1)-(4) Silurian, Devonian, Lower, and Middle Carboniferous:

(1) carbonate rocks; (2) clastic and clay rocks; (3) basalt and andesite; (4) acid volcanics; (5) Lower Paleozoic and Proterozoic; (6) ultramafic and gabbroid rocks of the oceanic basement.

were deposited in the Upper Paleozoic on the Kara-Kum platform massif. Elsewhere in what is now the Tien Shan, shallow-water and continental deposits of molasse type were forming at this time (fig. 9). Three series of rocks can be distinguished in the stratigraphic section of deposits of this epoch, separated by gaps in sedimentation. The lower series consists of clastic rocks, resting transgressively on the various tectonic units mentioned above and corresponding to the upper part of the Moscovian stage and the lower part of the Upper Carboniferous. The middle series consists of carbonate-terrigenous deposits and includes the greater part of the Upper Carboniferous and a part of the Lower Permian. The upper series is composed of coarse deposits belonging to Lower Permian.

Over the whole territory subjected to the Late Paleozoic mountain building granitic plutons were formed (fig. 9). In the Kara-Kum platform massif and the continental block composed of rocks of the northern miogeosynclinal zone, they formed in the Carboniferous and Permian. Elsewhere in the Variscan belt they formed during a more narrow age interval within the Permian. The granite plutons cut all the F_1 nappes and also the folded structures of the F_2 stage.

DEFORMATION OF THE F_3 STAGE

The structural forms determining the style of the F_3 stage deformations are strike-slip faults and horizontal folds. Thrusts, normal faults, and vertical folds accompany these principal structural forms. Deformations of the F_3 stage are unevenly distributed over the area of the folded system. They are most intense in the Fergana zone, the main structures of which are the Talasso-Fergana wrench-fault and the Fergana horizontal flexure.

The Talasso-Fergana righthanded wrench fault (figs. 3 and 6, nos. 24-25) cuts the Variscan geosynclinal system of the Tien Shan diagonally. The maximum amplitude of strike slip is about 200 km. The body of evidence for strike-slip movement along this fault has been analyzed by the author in a number of reports (Burtman, 1961, 1963, 1964). The amplitude of strike slip was determined by the displacement of facies zones of Devonian and Carboniferous deposits, massifs of plutonic Upper Paleozoic rocks, metallogenic zones, et cetera. The main movement along the strike-slip fault took place at the end of the Paleozoic and the beginning of Mesozoic.[3]

When vertical folds of the F_2 stage approach the strike-slip fault, they are compressed and sometimes overturned, and their hinges rise. The dips of faults become steeper near the strike-slip fault. The axial surfaces of vertical folds are curved near the line of the strike-slip fault so as to form horizontal folds, and these folds are oppositely oriented on opposite sides of the wrench fault. On the whole, the Talasso-Fergana

[3] Strike-slip movements were going on still later. Slight movements were recorded in the Jurassic. During the Cretaceous-Paleogene interval the amplitude of movement could have reached some tens of kilometers (Verzilin, 1968). Then strike-slip movements began again in the Pliocene and are still going on (Burtman, 1963, 1964; Rantsman, 1963).

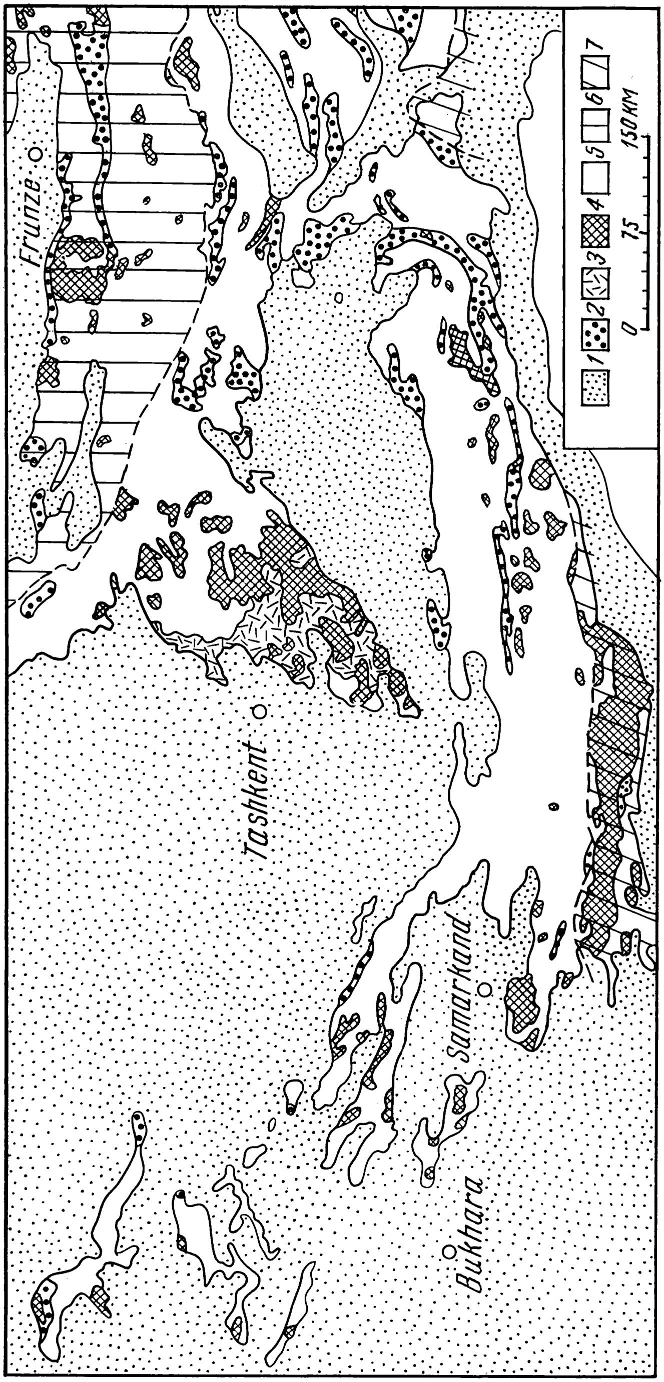


Fig. 9. Sketch of Late Paleozoic rocks.
(1) Mesozoic and Cenozoic; (2)-(5) Variscides: (2)-(4) Upper Paleozoic rocks of the mountain-building epoch: (2) clastic molasse, (3) acid volcanics and andesites; (4) granite granodiorite and syenite; (5) Middle and Lower Paleozoic and Precambrian; (6) Caledonides; (7) platform massifs.

wrench fault and the horizontal folds on its flanks are a combination of a righthanded horizontal flexure and a right-handed wrench fault that takes the place of the short limb of such a flexure. The total horizontal displacement of the Chatkal and Narym regions past each other is about 250 km; this includes the movement along the strike-slip fault and the displacement due to plastic deformation on its flanks.

West of this right-handed wrench fault and almost parallel to it is the short limb (figs. 3 and 6, no. 20) of the Fergana left-handed horizontal flexure. The southern hinge of the horizontal flexure, at the eastern end of the Alai range, is a tight, almost isoclinal horizontal fold outlined by axial surfaces of synforms and antiforms of the F_2 stage. In the core of this horizontal fold is a tectonic block (figs. 3 and 6, no. 18) that was squeezed out westward in the process of formation of this fold. This block is bordered by a right-handed strike-slip fault on the north and a left-handed one on the south. Eastward, in the East Alai and Fergana ranges the south hinge of the Fergana horizontal flexure is complicated by additional folding. The large Akbogus horizontal fold (figs. 3 and 6, no. 21), located here, is shown in figure 10. This horizontal fold is divided into two zones: inner and outer. The inner zone consists of seven arch-like tectonic blocks. The rocks within these blocks are compressed, forming vertical isoclinal folds, the axial surfaces of which are bent parallel to the faults bordering the blocks. The outer zone of the Akbogus horizontal fold deformed disharmonically relative to the inner zone. In the process of horizontal folding material was forced into the outer zone, producing the disharmony.

The northern hinge of the Fergana horizontal flexure is also complicated by secondary folds and strike-slip faults. North of the Fergana basin is a great tectonic block separated from more southern parts of the horizontal flexure by a left-handed strike-slip fault (figs. 3 and 6, no. 22). This block appears to have been isolated at the beginning of the F_3 stage and from then on was deformed independently. In this block one can see a pattern of crossing vertical folds (fig. 6). First synforms and antiforms of stage F_2 were bent to form a large horizontal fold that is a part of the Fergana horizontal flexure. Then, new vertical folds were formed in association with the Talasso-Fergana wrench fault. These vertical folds of the F_3 stage strike northwest or eastwest. Under these conditions, parts of F_2 folds that had the same strike were compressed, whereas other parts of the F_2 folds did not grow but were intersected by newly formed vertical folds of the F_3 stage.

Dislocations of the F_3 stage are widely distributed in the Kyzyl-Kum region as well. The folds of the F_2 stage have a persistent west-northwest strike in the Nurata region; in the eastern part of the Kyzyl-Kum region the strike of these folds is bent 20° northward at first, and then to the west again, outlining a gentle right-handed horizontal flexure (fig. 6). The western flank of the horizontal flexure appears in the structures of Tumdytau and east Bukantau, oriented at 40° relative to the short limb of the flexure. The length of the short limb is about 120 km.

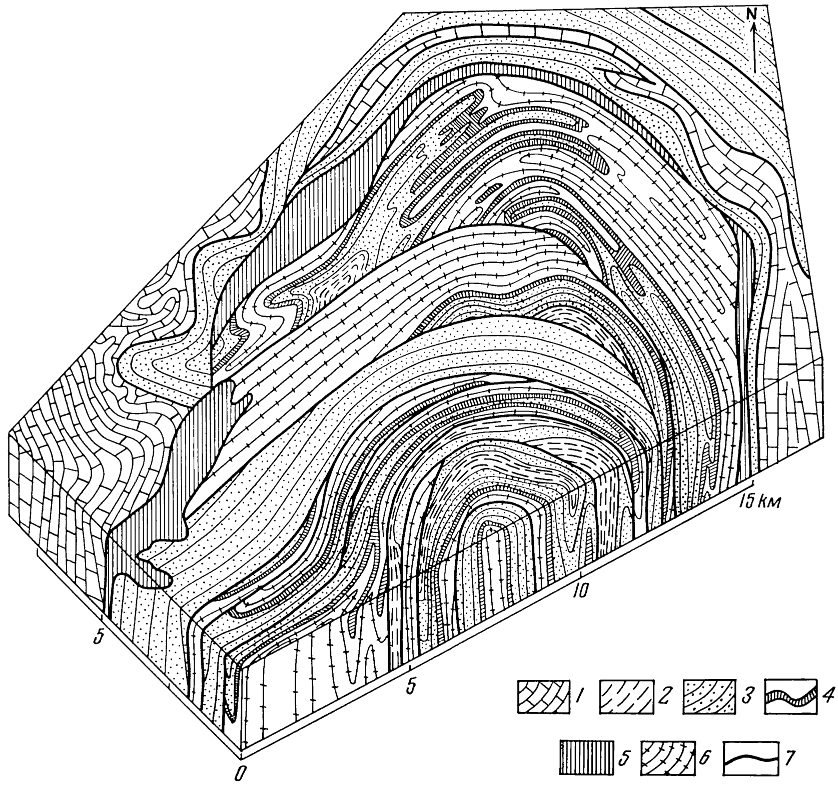


Fig. 10. Akbogus horizontal fold (no. 21, figs. 4 and 7).
(1) Upper Carboniferous; (2)-(3) Moscovian; (2) upper substage, (3) lower substage; (4) Namurian; (5) Devonian; (6) Silurian; (7) faults. The topography of the Earth's surface is not shown.

The western side of the Kyzyl-Kum is bordered by a left-handed strike-slip fault detected under the cover of the Meso-Cenozoic deposits by displacement of magnetic anomalies (Garkovets, Volfson, and Khivalovsky, 1967). It fits with the curve to the southwest of the latitudinal structures observed in the western part of the Bukantau upland. Thus the Kyzyl-Kum region is a block that was relatively displaced toward the north in the F_3 stage. The degree of dislocation of rocks in the strike-slip belts bordering this block is considerably greater than within the block. Inside the block the degree of dislocation increases toward the point of convergence of the strike-slip belts; thus the folds are overturned northward in the Bukantau upland.

The Kyzyl-Kum block occupies a position in the angle between the meridional structures of the Urals and the latitudinal structures of the Tien Shan, and the above structural features of the Kyzyl-Kum appear to result from disharmonious folding due to compression of that angle.

REGIMES OF DEFORMATION OF THE VARISCAN TIEN SHAN

The tectonic forces controlling the deformations of the Variscan geosynclinal system of the Tien Shan in the F_1, F_2, and F_3 stages were oriented horizontally in a nearly meridional direction. Deformations of the F_1 stage are related to the closure of the oceanic structure and the smashing together of the north and south continental blocks. At this stage, a contraction of the geosynclinal system in the transverse direction took place; it was carried out by overthrusting. Folded structures were formed at this stage entirely within the sheets or stacks of sheets.

By the beginning of stage F_2 the north and south continental blocks had closed up and overall deformation of these blocks could begin, involving combined deformation of all tectonic units including the basement. In stage F_2 the geosynclinal system continued to contract transversely by the formation of vertical folds. Deformations at the F_2 stage resulted in considerably less change of dimensions of the geosynclinal system as compared to deformations of F_1 stage.

Both overthrusting and formation of vertical folds went on under the same deformation regime, producing in both cases a transverse contraction of the geosynclinal system which was compensated by its elongation (thickening) along the vertical axis. By the end of stage F_2 the system could no longer deform under this regime so that, in passing to the F_3 stage, a radical change of the deformation regime occurred. At this stage the meridional compressional forces led to a redistribution of masses (elongation) in the horizontal direction. The change of regime was accompanied by a change in the distribution of deformation. Deformations of the F_1 and F_2 stages were distributed relatively evenly throughout the geosynclinal system, whereas deformations of the F_3 stage were localized in certain zones, the most significant of which are indicated on figure 6. In many other areas such deformations are entirely absent, or their intensity is much lower than that in those zones.

Deformations of the F_2 stage led to the uplift and the formation of dissected topography. At stage F_3 the redistribution of material took place in the horizontal plane, whereas the neutral axis of deformation was vertical. With such an orientation of the principal axes of deformation it was not at all necessary that the fold formation should be accompanied by mountain building; instead there was a transition to the platform stage of development of the region.

ON THE EVOLUTION OF THE FOLDING PROCESS

In the Variscan Tien Shan the formation of folded structure began with the appearance of nappes and recumbent folds. The deformation of this first stage was accompanied by accumulation of flysch, wildflysch, and olistostrome deposits. At the second stage there appeared vertical folds, high-angle reverse faults, and thrusts. Folding proceeded simultaneously with accumulation of molasse deposits. Mostly horizontal folds and strike-slip faults, accompanied by thrusts and normal faults, formed at the third stage. The attribution of deformations of one or another style to a certain stage is certainly not absolute; one can speak only of a general trend in the development of deformations. The given sequence of deformations is not peculiar to the Variscan Tien Shan. Some other examples of a similar evolution of Paleozoic deformations that took place during one tectonic cycle are given below.

A number of folding stages have been distinguished in the Caledonides of various regions of North Scotland, reaching eight in some areas (Anderson and Owen, 1968; Bennison and Wright, 1969). Nappes and recumbent folds formed in the earliest stage of deformation (Bailey, 1910, 1922, 1960, et cetera.; Johnson, 1965; Kennedy, 1955; Rast, 1963; Ramsay, 1963; Sutton and Watson, 1962); then, during some stages, vertical folds were formed (Clifford, 1957; Johnson, 1965; Johnstone, 1966; Rast, 1963; and other papers); and in the last stage horizontal folds formed associated with strike-slip faults (Bailey, 1934; Clifford, 1960; Powell, 1966; Ramsay, 1958; Rast, 1963; Simpson, 1968).

The evolution of the folding process in the Caledonides of Scandinavia and Spitsbergen was analogous. At first nappes and recumbent folds were formed (step I); later, they were folded into synforms and antiforms (step II) (Bennett, 1970; Binns, 1967; Holmes, 1966; Hossack, 1967; Ramsay, 1971; Rutland, 1959; Strand, 1960; Wells and Bradshew, 1970, et cetera). In some areas, as in Scotland, several stages of vertical folding were distinguished (Gayer, 1969; Hooper and Gronov, 1970; Ramsay, 1971; et cetera). In the latest step folding took place in a horizontal plane (Gayer, 1969; Harland, 1959; Vogt, 1955).

A similar succession of dislocations has been established in the Paleozoic folded structures in the northern part of the Iberian peninsula (Bosh, 1969; Julivert, 1971; Sitter, 1960, 1967). In the South Appalachians during the Alleghenian tectonic epoch, nappes were folded into a system of vertical folds (Rodgers, 1970). These structures were later disturbed by strike-slip faults and smooth curves in the horizontal direction (King, 1955, 1964; King and Ferguson, 1960; Rodgers, 1950; and others). The same sequence of dislocations takes place in Mesozoic and Cenozoic folded zones (Burtman, 1970, 1972) as well.

All these examples refer to linear folded systems, that is, systems that are relatively narrow and underwent an intense transverse contraction. Non-linear mosaic folded systems belong to another type (Peive, 1960; Zonenshain, 1967). The Paleozoic structures of Central Kazakhstan may serve as an example of these systems. The dimensions of this system were considerably less altered in the folding process. As the largest transverse contraction of the system occurs through overthrusting, one may expect that in mosaic systems the dislocations of step I are not pronounced or are entirely absent.

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in 1967; at that time the ideas of overthrusting in the Variscan Tien Shan had few followers, and his support was inspiring.

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