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Kinematics of the Arabian Syntaxis

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Primary and secondary structural arcs participate in the structure of the syntaxis. The following were formed in the Neogene: the East Taurus arc and a system of conjugate arcs disharmonic with respect to it, including the Khorasan, Elbrus, Lesser Caucasus, and Trabzon arcs. The South Caspian and West Kopet Dag arcs developed in the Quaternary. Development of the structural arcs is the result of crustal flow along the Alpine belt caused by the approach of the Arabian plate to Eurasia. Transverse shortening of the Alpine belt over hundreds of kilometers occurred as a result of collision of the plates in the region of the syntaxis. When this happened, the Lesser and Greater Caucasus were thrust over the Rioni-Shirvan microplate.

The Arabian syntaxis is formed of tectonic zones of the Alpine belt that envelop the Arabian platform. All modern models of tectonic development of this syntaxis presume approach of the Arabian plate to Eurasia [1, 2, 10, 24, 26, 32, 40 and others]. However, the scale and time of these displacements and the method of development of the structure of the syntaxis are at issue. Many researchers explain the internal structural characteristics of the syntaxis by interaction of microplates [8, 15, 25, 33 and others]. The boundaries of the microplates are determined according to seismic data. Dispersed seismicity is characteristic of the region under discussion, for which reason the location of these boundaries is not unequivocal. Boundaries having an anti-Caucasian (northeasterly) trend are poorly substantiated. Such boundaries locally bear traces of tectonic deformations that compensate for the inferred mutual displacements of the microplates.

In this article we discuss the kinematics of the Arabian syntaxis based on analysis of the structural plan of the region. This analysis has demonstrated a major role for tectonic flow of crustal rocks during development of the syntaxis.

BOUNDARIES OF THE SYNTAXIS

The Arabian syntaxis can be defined as a region of narrowing of the folded belt that was caused by approach of the Arabian continent to Eurasia. In a structural-geological respect this is a region of structural arcs located to the north of Arabia. Understood in this fashion, the southern boundary of the syntaxis is the edge of the Arabian platform and the eastern boundary the Lut block. In the west, it is reasonable to delimit the syntaxis by the meridian passing through the crest of the Cypriot arc.

The northern boundary of the syntaxis separates the region of development of structural arcs and the regions where there are no large structures of this type. In the Caucasus this boundary separates the Lesser Caucasus structural arc from the Rioni-Shirvan microplate and the linear fold system of the Greater Caucasus. This is the Pontus-Caspian tectonic suture. Its exposed part is known as the Surami-Gokishur overthrust [11]. It serves as the boundary of the Adzhar-Trialet zone of the Lesser Caucasus with the Georgian block, which is part of the Rioni-Shirvan microplate. B. F. Meffert [21] considered this overthrust the front of a nappe. This fault was later viewed as a reverse fault that is the surface manifestation of a steeply dipping deep fault [27 and others].

Field studies have shown that the Surami-Gokishur fault represents a combination of tectonic dislocations of different types [6]. In the eastern part (from Surami to Khidari) on the southern boundary of the Dzirul massif, the line of rupture has a meandering contour. It extends sublatitudinally and, as a whole, coincides with the strike of the Upper Cretaceous and Eocene beds that form the nrothern periphery of the Adzhar-Trialet zone. The Cretaceous, Paleogene and Miocene deposits to the north of the fault dips southward from 30 to 60°. It dips steeply relative to the bedding of the southern limb of the fault and is discordant with the beds of the northern limb. Drag folds are developed in the rocks of the hanging wall, indicating northerly motion of this limb.

This rupture has a northwesterly trend in the middle section (from Khidari to Pirveli-Sviri). It is oriented obliquely to the general trend of the volcanogenic formations of the Adzhar-Trialet zone. The fault line is relatively linear. The offset dips to the southwest from 45 to 75°. It dips steeply against bedding and cuts the rock beds that form the two limbs of the fault. In the southwestern limb the beds of volcanogenic rocks

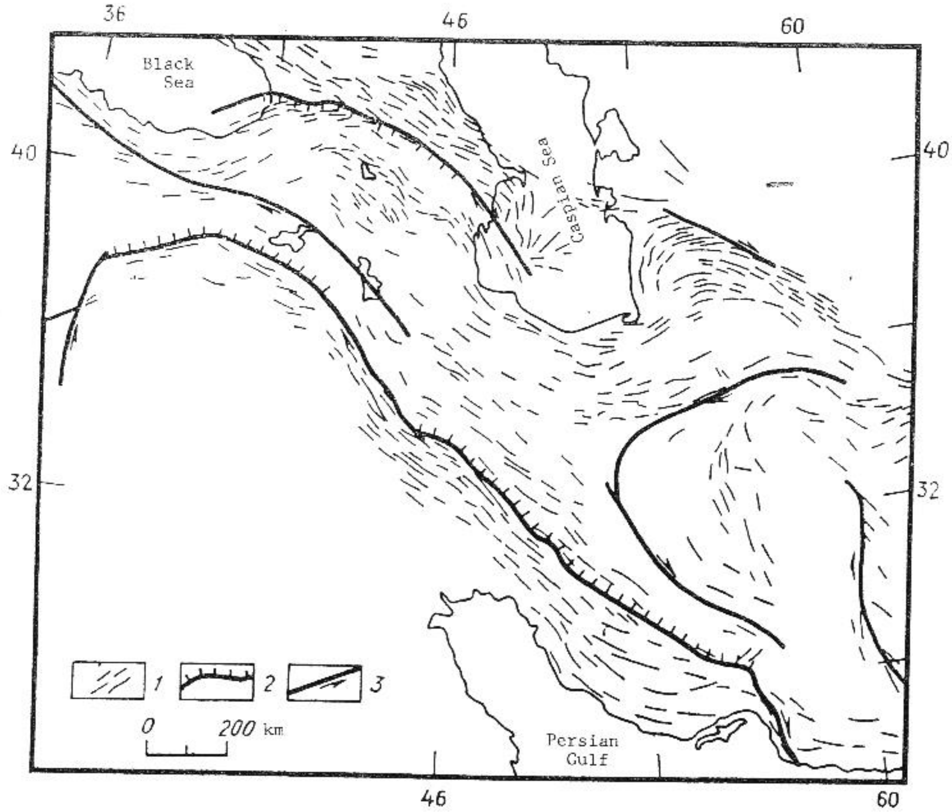

Fig. 1. Alpine folds of the Arabian syntaxis.

1) Fold axes (according to geological and tectonic maps of the Caucasus and Iran); *2*, *3*) main faults: *2*) overthrusts, *3*) strike-slip faults.

and the fold axes change their latitudinal strike to southeasterly on approaching the fault. They "adapt" to the strike of the dislocation. Such structural relations indicate the right-lateral character of the movements in the middle section of the Surami-Gokishur fault. In addition to offset, this dislocation also has an upthrown component.

To the west, the strike of the Surami-Gokishur fault again becomes latitudinal and its line meanders. The offset dips to the south 20 to 50° and is almost concordant with the beds of the hanging wall of the fault. The structural characteristics of the adjacent part of the Adzhar-Trialet zone and drilling data suggest that this fault serves as the front of the Sakraul nappe in the Khanis-Tskali basin, thrust over the rocks of the Georgian block [6]. Farther to the west the frontal overthrust, converting to nappes, is traced to the Black Sea. In Gurii the basement of the nappe has been found in oil exploration wells at depths greater than 2 km [5].

Thus, the Pontus-Caspian tectonic suture has the characteristic of an overthrust in its exposed part. To the west of the Dzirul massif the frontal overthrust of the Adzhar-Trialet zone is concealed beneath the Quaternary deposits of the Kartliisk depression. Farther to the east, the northern part of the Adzhar-Trialet zone is covered by nappes of the Greater Caucasus system facing southward, which are developed in the eastern part of the Kartliisk depression and in Gare-Kakhetiya. The Caspian segment of the Pontus-Caspian tectonic suture is probably a strike-slip fault.

The tectonic results of approach of the Arabian plate to Eurasia extend far beyond the boundaries of the syntaxis. In the north they encompass the Greater Caucasus, the Alpine deformations of which were caused by approach of the Rioni-Shirvan microplate to Eurasia. Because of the marginal overthrust, this plate functioned as a buffer, preventing development of large structural arcs in the Greater Caucasus. In the west, as a result of collision of Arabia and Eurasia, Asia Minor was rotated and moved northward. The result of this displacement was development of the structural arcs of the Carpathian-Balkan region [7, 30].

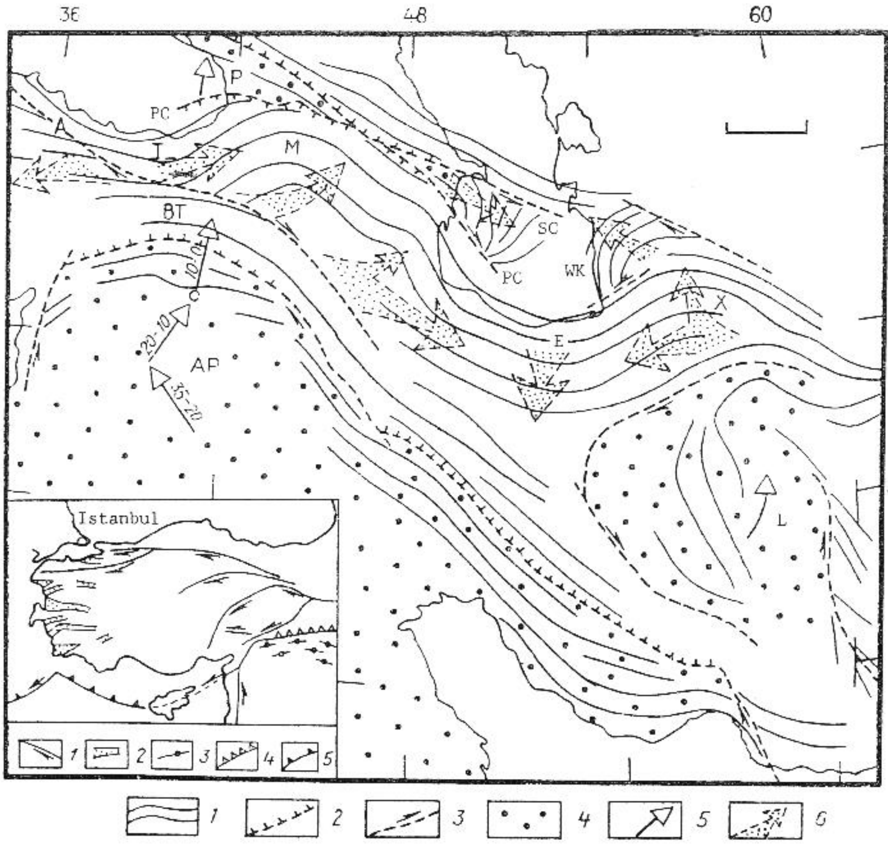

Fig. 2. Structural scheme of the Arabian syntaxis and neotectonic scheme of Asia Minor (inset).

1) Directions of axes of Alpine folds; *2*) main overthrusts; *3*) main strike-slip faults; *4*) Arabian plate (AP), Lut (L) and Rioni-Shirvan (R) microplates; *5*) directions of motion; *6*) directions of tectonic mass flow. Structural arcs: BT) East Taurus, WK) West Kopet Dag, M) Lesser Caucasus, T) Trabzon, X) Khorasan, E) Elbrus, SC) South Caucasus, A) Anatolian strike-slip fault, PC) Pontus-Caspian tectonic suture. Direction of motion of the Arabian plate relative to Eurasia determined by L. P. Zonenshayn [according to 36] for a point with coordinates 37°N latitude, 41°E longitude. Inset [37]: *1*) strike-slip faults; *2*) grabens; *3*) folds on the edge of the Arabian plate; *4*) overthrusts; *5*) subduction zones on the sea bottom.

STRUCTURAL ARCS OF THE ARABIAN SYNTAXIS

Let us now consider the structural plan of the Arabian syntaxis (Fig. 1). The axes of the Alpine folds delineate structural arcs, the chief ones of which are as follows (Fig. 2).

The East Taurus arc is outlined by the structures of the eastern Taurus and southern Kurdistan. The crest of the arc faces north. The following structural elements run parallel within this arc: folds in the cover of the Arabian platform, the edge of the Arabian platform, and folds of the Alpine belt on the edge of this platform. Such relationships indicate development of folds of the structural arc as a result of the direct pressure of the edge of the Arabian plate.

To the east and north of the East Taurus arc we find a system of conjugated arcs, including the Khorasan, Elbrus, Lesser Caucasus and Trabzon arcs. The Khorasan arc is formed by structures of the Turkmen-Khorasan Mountains and the eastern Elbrus, its crest facing north. The Elbrus arc is formed from structures of the Elbrus and Bogro dag with its crest facing south. The Lesser Caucasus arc has a northward facing crest. The Trabzon arc is outlined by the folds of the eastern Pontides with its crest facing south. This system of conjugate arcs (the KELT system of arcs) is disharmonic relative to the East Taurus arc and borders it along the offset. The KELT system of arcs is also disharmonic relative to the structures developed to the north of this system.

Paleomagnetic studies show [4] that the Lesser Caucasus arc is secondary: It formed after development of the folds that outline it. During development of the arc these folds were reoriented (rotated). The Elbrus and Trabzon arcs, conjugate with the Lesser Caucasus arc, probably also have a secondary origin. Paleomagnetic studies in the eastern Potides [39] speak in favor of this origin for the Trabzon structural arc.

The Alpine structures of the Turkmen-Khorasan Mountains probably developed as a result of movement of the Lut microplate northward (see Fig. 2); they have their original strike. Studies in Kopet Dag, on the eastern limb and at the crest of the Khorasan arc, show that the paleomagnetic vectors have kept the same location since the Early Cretaceous [3]. Solutions of the focal mechanisms of earthquakes indicate probable displacement of the Lut block in a northerly direction in Recent time [34]. Tectonic flow directed westward from the region of approach of the Lut massif to the Eurasian plate was the result of this displacement. The results of this tectonic flow are reflected in the disharmonic structure of the Khorasan arc, the external part of which is steeper than the internal region.

The folds that developed in the Alpine cover of the Lut block also delineate a structural arc. Its crest faces northwest. According to paleomagnetic data [29, 31] the Lut block was rotated in a counterclockwise direction. These folds originally might have had bent axes that conformed with the western boundary of the block. During subsequent rotation of the block, these folds were reoriented and the gently sloping primary structural arc was converted to a steeper secondary arc.

The west Kopet Dag and South Caspian structural arcs bound the KELT system of arcs in the northeast. The West Kopet Dag arc (see Fig. 2) is delineated by the axes of folds formed by Cretaceous, Tertiary and Quaternary deposits. The crest of the arc faces west. It is disharmonic relative to the Khorasan and Elbrus arcs. The South Caspian structural arc is delineated by the axes of folds that developed in the Pliocene-Quaternary deposits on the bottom of the Caspian Sea. The crest of the arc faces east. It is disharmonic relative to the Lesser Caucasus and Elbrus arcs. The West Kopet Dag and South Caspian arcs are mirror images and have identical structural relations with the KELT arc system. Paleomagnetic studies [3], conducted on the northern limb of the West Kopet Dag arc, revealed that the folds have an unchanged strike here. Consequently, the transverse position of the South Caspian arc relative to the Khorasan arc is primary. Such relationships are likely between the South Caspian and Lesser Caucasus arcs. In addition to those listed, a large number of small structural arcs that are usually combined with strike-slip faults are located in this region.

Thus, structural arcs of three types are developed within the Arabian syntaxis: a) the East Taurus and Khorasan structural arcs that enclose the Arabian plate and the Lut microplate; b) the Trabzon, Lesser Caucasus and Elbrus structural arcs, disharmonic with respect to the edge of the Arabian plate and the East Taurus arc; and c) the West Kopet Dag and South Caspian structural arcs, disharmonic relative to the KELT arc system. The folds of the East Taurus arc formed under the direct influence of the edge of the Arabian plate. The disharmonic secondary arcs could only develop as a result of tectonic flow along the Alpine belt. The character of the disharmony between the Lesser Caucasus and East Taurus arcs indicates mass flow from the crest of the syntaxis in an easterly direction. Rotation of the Lut block and its northward movement caused a counterflow (see Fig. 2). Material was also compressed from the arc of the Arabian syntaxis in a westerly direction, as indicated by the very recent structure of Asia Minor (see inset in Fig. 2).

The West Kopet Dag and South Caspian arcs are derivatives with respect to the arcs of the KELT system. The folds within these arcs developed as a result of compression of material from the northward advancing crests of the Lesser Caucasus and the Khorasan structural arcs. The origin of the West Kopet Dag and South Caspian arcs as a result of horizontal extrusion was argued by M. L. Kopp [18, 19].

The front of the Lesser Caucasus arc faces the East European platform. In this respect, it is similar to the Carpathian structural loop, whose front also faces the platform. In both regions this front is formed by nappes. At the same time, development of structural arcs in these regions occurred under different conditions. In the Carpathian-Balkan region the horizontal deformations, accompanied by virgation of the tectonic structures and overthrusting, fully enclosed the folded belt, and its marginal parts were "splattered out" onto the platform. As a result a rootless folded system and a deep foreland depression superimposed on the platform structures developed. In the Caucasus the horizontal deformations that led to development of the structural arcs did not go beyond the Alpine belt and did not reach its northern boundary. The Carpathian region lies in an area of injection of crustal masses, whereas the Arabian syntaxis is a region of outflow (compression) of crustal masses. These differences in conditions of deformation led to differences in shape and dimensions of the structural arcs of the Carpathian-Balkan and Pontic-Lesser Caucasus regions.

DEVELOPMENT OF THE SYNTAXIS

The onset of orogenesis in the region of future syntaxis is assigned to the Late Eocene-Early Oligocene. By this time, the Arabian plate had approached Eurasia and moved northwesterly along its boundary [36]. With this direction of relative displacement, interaction of the plates was limited and deformations of the Pyrenean (Trialet) phase were relatively weak in the Caucasus. At the same time, they concompassed an extensive area of the belt as far as the Greater Caucasus [10].

In the Early Miocene the direction of displacement of the Arabian plate relative to Eurasia changed to north-northeast (see Fig. 2), and collision of these lithospheric plates began. It is natural that the most intense Early Miocene deformation occurred on the southern boundary of the Alpine belt, where folds and the extensive Taurus and Zagros nappes formed. The East Taurus structural arc developed when the Arabian plate moved northward. Development of folds within this arc continued later: Pliocene deposits also participate in the marginal folds of the Arabian platform [16].

The folds of the Lesser Caucasus and Iran developed in the Miocene and were then deformed into the structural arcs of the KELT system. The onset of folding in the Kurin depression is assigned to the Late Miocene [22]. The youngest deposits covered by the frontal overthrust of the Adzhar-Trialet zone have the same age (Upper Sarmatian). Apparently, overthrusting of the Lesser Caucasus onto the Rioni-Shirvan microplate was already occurring in the Late Miocene. Northward movement of the Lesser Caucasus, in turn, is associated with development of the Lesser Caucasus structural arc. This enables us to assign the onset of development of the arcs of the KELT system to the Miocene, although the main stage of their development is later.

In the eastern part of the Adzhar-Trialet zone we can see a sharp angular disconformity between the Lower and Upper Pliocene deposits (before the Akchagylian). By the Late Pliocene the folded structures of Adzhar-Trialet had formed [6]. By this time the overthrust of the southern slope of the Greater Caucasus was created [12, 20]. The main stage of approach of the tectonic zones of the Lesser and Greater Caucasus by their overthrusting onto the Rioni-Shirvan microplate probably took place in the Pliocene. At the end of this process the overthrusts of the Greater Caucasus and Lesser Caucasus systems met opposite the crest of the arc (at Gare-Kakhetiya) and the first system partially covered the second (Fig. 3).

The South Caspian and West Kopet Dag arcs formed in the late stage of development of the KELT system of arcs. Development of folds in the South Caspian and West Kopet Dag arcs has been occurring in the Quaternary.

The magnitude of transverse shortening of the Alpine belt in the zone of the Arabian syntaxis has been estimated in different ways. The width of the Tethys Ocean in the Late Cretaceous according to data from some palinspastic reconstructions was 1,000 km [10, 28], from others—4,000 km [13]. Data obtained according to strip magnetic anomalies of the Atlantic Ocean bottom are significant. Analysis of displacements of the African-Arabian and Eurasian plates during

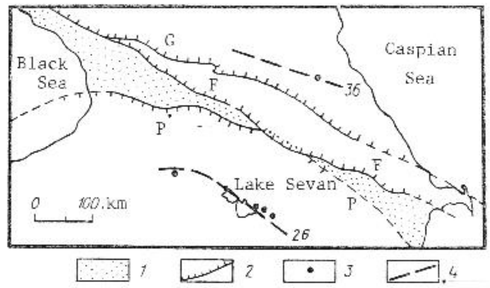

Fig. 3. Late Alpine overthrusts of the Caucasus.

1) Rioni-Shirvan microplate; *2*) late Alpine tectonic sutures; P) Pontus-Caspian, F) front of Greater Caucasus nappes, G) Main Overthrust of the Greater Caucasus; *3*) points of paleomagnetic determinations according to [4]; *4*) Late Cretaceous paleomagnetic latitudes.

opening of the Atlantic permits determination of the size of the Tethys Ocean [32, 36, 36]. According to these data the distance between the Arabian plate and the Scythian platform in the Late Cretaceous was about 2,000 km, which is consistent with the results of paleomagnetic studies. Comparison of the paleomagnetic latitudes of the Late Cretaceous on the Arabian plate and in Dagestan on the northern boundary of the Alpine belt permits determination of the width of the belt, which at this time was 2,450 ± 450 km [4]. Comparison with the modern picture leads to the conclusion that in post-Cretaceous time, transverse shortening of the Alpine belt by 1,800 ± 450 km occurred in the region of the Arabian syntaxis.

The Lesser Caucasus branch of the Mesozoic Tethys was closed in the middle of the Cretaceous. This process was accompanied by abduction of Sevan ophiolites on the northern flank of the former oceanic basin and the Vedin ophiolites on its southern flank. In the Lesser Caucasus, abduction of ophiolites occurred in the Cenomanian-Coniacian, in Asia Minor—as late as the Campanian [17, 35]. Beginning in the Late Cretaceous, there are no signs in the Caucasus region of oceanic crust. All subsequent deformations are reflected in the Recent structure of the region, since from this time tectonic processes occurred within continental crust (continental, subcontinental, thinned continental). In this connection, we should touch on the question concerning how shortening of the crust in the Caucasus region occurred.

The Late Cretaceous paleolatitude of Limestone Dagestan, determined according to remanent magnetism, was 36±2°N latitude, that of the Lesser Caucasus—26±3°N latitude [4]. The modern distance between these regions is 2° (see Fig. 2). Consequently, paleomagnetic data indicate post-Cretaceous approach of the Lesser Caucasus and Scythian platforms by 8±3°, i.e., by a distance of 900±350 km.

Folds and overthrusts of the Greater Caucasus are assigned a major role in compensating for this transverse shortening of the region. The reduction in width of the Greater Caucasus as a result of development of the Alpine folds is estimated at 80-120 km [14]. The largest overthrust structures of the Greater Caucasus are the Main Overthrust and the nappes of the southern slope (see Fig. 3). The Main Overthrust is traced along the entire Caucasus Range. In the western Caucasus, metamorphic rocks of the main Caucasus Range were overthrust onto the flysch zone of the southern slope. The visible amplitude of overthrusting is as much as 20 km. The true magnitude of overthrusting is much greater, since a significant portion of the flysch zone is covered by overthrusting: The tectonic subzones approach the overthrust line at an angle and emerge beneath it [14, 26].

The nappes of the southern slope developed in the frontal part of the Caucasian flysch zone. The total amplitude of the napes in Gornaya Kakhetiya is 60 km. It is thought that the amount of allochthonous displacement to the west diminishes and reaches zero northwest of Rioni [12]. It is difficult to agree with the latter conclusion. Sharply differing facies of Middle Jurassic deposits in the immediate vicinity of each other can be seen along the right tributaries of the Rioni River (Lukhuni-Tskali, Sakaura). The southern facies of the Bajocian are represented by a 2-kilometer bed of tuff-breccias, tuffs, lava-breccias with layers of basalts, whereas the northern facies are represented by argillaceous shales with interlayers of marls and sandstones, among which only certain interlayers have a tuffite origin. In the Recent structure these facies are located 2 to 6 km from each other, which allows us to presume significant tectonic apporach. It seems likely that the tectonic covers and sheets of the southern slope, developed in Gornaya Kakhetiya and South Ossetia are replaced to the west by a single tectonic surface (or a narrow tectonic zone), along which the flysch zone of the Greater Caucasus is overthrust onto the Rioni-Shirvan microplate. The amplitude of the displacement is probably comparable to the total amplitude of the Kakhetiya nappe. East of the Rioni River this tectonic suture can be seen along a line that follows a northwesterly direction through the district of Utsery in the Sakaura River valley and the upper reaches of the Lukhuni-Tskali River. This tectonic line then probably passes along or close to the southern contact of the Diz series and unites with the Main Overthrust west of the Inguri River.

The total amplitude of transverse shortening of the tectonic zones of the Greater Caucasus from the form of structures visible on the surface is about 200 km. It is reasonable to assume that the nappes of the southern slope are a surface manifestation of a deep nappe along which the Greater Caucasus was overthrust onto the Rioni-Shirvan microplate [14, 23, 26]. Acceptance of this hypothesis increases the magnitude of transverse shortening of the tectonic zones of the Greater Caucasus to 250-300 km.

The above-mentioend data and considerations enable us to conclude that the Alpine deformations of the Greater Caucasus do not compensate for the entire magnitude of approach of the Lesser Caucasus and Scythian platforms determined by the paleomagnetic method. The Pontus-Caspian tectonic suture probably has a major role in solving this problem of space. In contrast to all other faults of the Caucasus, this tectonic suture separates regions with sharply differing structural features. We can imagine that the rocks of the Lesser Caucasian structural arc occur in the form of an allochthon that covers the southern part of the Rioni-Shirvan microplate. In this case the overthrusts and nappes on the northern boundary of the Adzhar-Trialet zone are the surface manifestation of a deep nappe.

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