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The Structure and Evolution of the Sura–Kama Strike-Slip Zone in the Cainozoic (the Volga–Ural Anteclise of the East European Platform)

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Abstract—The Sura–Kama zone (SKZ) complicates the central area of the Volga–Ural anteclise and extends sublaterally from the Sura River basin towards the Kama River at a distance of 700–750 km. Based on the analysis of geological–geophysical data and structural studies, a model for the tectonic structure and the evolution of the SKZ is developed. This is a deep tectonic fault that shows the features of long–term polystage development. During the latest Cimmerian–Alpian period of tectonic activation, the SKZ represented a zone of strike-slip and consecutive manifestation of early transpressional right-lateral strike-slip dislocations that changed to left-lateral strike-slip displacements under transtension conditions as a result of kinematic inversion. Features of the inhomogeneous structure of the SKZ are revealed. The segments formed by the system of strike-slip duplexes are alternated along the strike by the principle of rotation–fold and "domino" structures. The particular models of evolution of these segments are proposed by the examples of the widely known Karlin, Tetyushin and Lower Kama dislocations. It is assumed that kinematic inversion and compression–decompression phenomena on the flanks of the SKZ, as well as the tectonic environments in the area of its dynamic influence were highly important for the development of the processes of migration and redistribution of hydrocarbon components.

Keywords: intraplate tectonics, geodynamics, strike–slip zone, kinematics, structural paragenesis, platform, Karlin structure

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INTRODUCTION

As geological data accumulate, an increasing amount of information about the intratectonic mobility of lithospheric plates, including those having ancient continental crust, becomes available. One of the grounds for the substantiation and the development of the ideas about the intraplate geodynamics is the Volga–Ural anteclise of the Eastern European platform (EEP). A large volume of geological and geophysical studies, as well as a dense network of drilled wells in the oil-field areas of these regions made it possible to identify alpine-type structural ensembles, which are anomalous for the platform [5, 6, 8, 11, 13, 14, 15, 20–23, 26, 33, 34, 36]. For the genesis of these structures, glaciodynamic, tectonic, and meteorite models of their formation are proposed.

In accordance with the tectonic concepts the Volga–Ural province is considered a certain anomalous segment of the EEP, which is prone to intense tectonic activation at the plate and especially the neotectonic stage of development [5, 6, 8, 11, 13, 20–23, 29, 30, 35]. Many researchers explain this activity by the conditions of action of horizontal compression tectonic stresses propagating from the fold regions surrounding the platform: the Ural region, from the east and the Caucasian region, from the south [5, 6, 14, 15, 21–23, 36]. Here, particular ideas about the regional tectonics differ significantly. The dislocations of the nappe are considered a combination of subisometric arcogenic and linear overthrust systems [13–15] and mostly in the form of strike-slip structures [21, 23]. In addition to the theoretical content, developing the concept about the mechanisms for the formation of structural ensembles of this region is also of practical importance. It is known that many Volga–Ural hydrocarbon deposits are localized in the traps of a structural type, and the character of paleostresses and the structural morphology itself control hydrodynamic features of the occurrence of oil and gas clusters in many respects [1, 11, 14, 26, 37].

In this work we consider the tectonic features of the Sura–Kama zone of strike-slip dislocations, which holds one of the key positions in the tectonics of the central segment of the Volga–Ural province. It includes several structures that are anomalous for the platform and are known as Karlin, Tetyushin, and Lower Kama dislocations, provoking interest and discussions among a wide range of geologists (Fig. 1).

The research procedure. The Sura–Kama zone was examined by the methods of distance study of the structures: identifying digital maps of the relief, aerospace images, maps of magnetic and gravimetric anomalies. The preliminary kinematic identification of the faults was carried out based on the analysis of a fabric (according to [21, 27]). The results of the distant analysis were specified by the field studies using the methods of structural–kinematic and paragenetic analyses whose methods were considered previously [17–19, 21, 24]. The statistical processing of the kinematic data was performed using the FaultKin6 [40].

COMMON FEATURES OF THE SURA–KAMA ZONE (SKZ) TECTONICS

The eastern segment of the Sura–Kama zone is studied relatively well and is known under the name of the Lower–Kama (Kama region) fracture located in the lower-middle reaches of the Kama River [2, 4, 8, 11, 37, 39]. R. Valeev [6] suggested identifying the Sura–Kama zone as a broad area of development of upthrow–overthrust structures covering a significant part of the Middle Volga region. We consider the SKZ within the narrower space: as a zone 50–60 km wide that extends sublaterally from the Sura River basin to the valley of the Kama River at a distance of 700–750 km (Fig. 1).

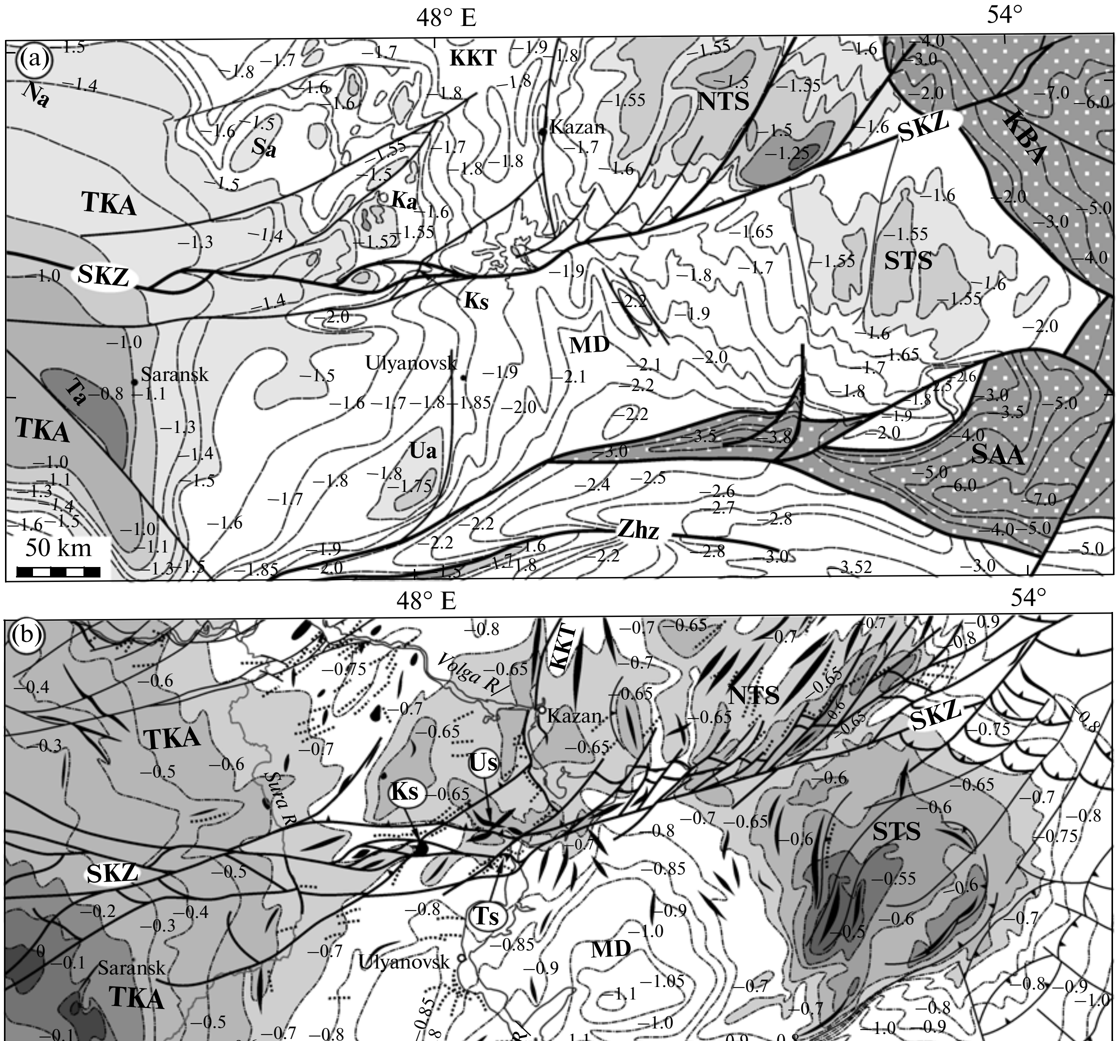
The Sura–Kama zone participates in the structure of all platform stages (Fig. 1). In the Precambrian granulite–gneiss basement, this zone partly conforms to the Elabuga–Bondyuzh belt separating the Northern and Southern Tatar (Almetyevsk) ovoids, along the boundaries of which the system of SE-vergence overthrusts is logged [2, 9]. At the level of the roof of the Precambrian basement, the SKZ is one of the main structures complicating this surface. In the eastern segment, it separates the northern and southern scarps of the Tatar arch and aligns with the narrow basin [11, 39]. The central segment of the SKZ complicates the region of joining the Kazan–Kazhim trough and the Melekess depression in the region of the Kazan saddle. In the west, the zone breaks up the structure of the eastern slope of the Tokmov arch and separates some of its apices into the northern (Kanashi, Sundyr, etc.) and the southern (Ulyanovsk and Tokmov) groups (Fig. 1a).

These tectonic features are also mainly recurrent in the structure of the Phanerozoic cover, but in this case several structures of the higher order disappear and the new structural forms appear. In particular, there are large and small swell-like structures that emphasize structural features of a larger rank (Fig. 1b). In the Southern Tatar scarp, the orientation of the swells reflects its oval–concentric and eddy structure. In the area of the Northern Tatar rise they are steadily linearly NE-oriented along the strike of the fractures feathering the main fault of the SKZ [8, 11, 14]. The meridional orientation of the swells from the Kazan–Kazhim trough southward of the SKZ changes to a fan-shaped occurrence in the region of the Melekess depression. In the majority of cases, the orientation of the swells sharply changes inside the SKZ itself and acquires a regular en-echelon character, and the axes of the compression structure (mesofolds and swells) deviate from the main fault of the SKZ counter clockwise in the most cases, which in general resembles the fabric of the right-lateral strike-slip zones (Fig. 1b).

On the Earth's surface, judging by the identified digital map of relief and space images, the SKZ has a complex structure, striking inhomogeneously, and in general aligned with the structure of the deep levels (Fig. 1c). At the western and eastern flanks of the zone, regions of its fan-shaped virgation and probable flattening are identified. In the eastern segment, the SKZ's main fault is feathered by NE-trending fractures and blocks separated by them forming a structure that resembles domino tiles, which is highlighted by the morphology of the Kama River valley [11]. The SKZ bends slightly at the confluence of the Kama and the Volga Rivers and has a latitudinal trend and lens-shaped internal structure to the west of the bend. In the western segment of the zone, there are asymmetric lenses resembling strike-slip duplexes in terms of morphology. The large bodies of the duplexes many tens of kilometers in size are often composed of minor, similarly shaped lenses, which indicate a fractal principle of the similarity of different-rank structures (Fig. 1c).

The structural features of oil-bearing swell-like structures in the SKZ and its margins point to the complex conditions of their formation [4, 5, 11, 13, 14, 34]. Drilling materials show that the morphology and the position of these structures often change along the section from bottom to top. It is frequently recorded that the axes of the apical parts of the swells show horizontal displacement relative to their lower root parts. For example, the Uleminsk swell developed in the central segment of the SKZ, the amplitudes of such displacements reach 6–10 km (Fig. 2). In this case, this swell is formed by complex structural dis-

Fig. 1. Structural schemes of the Volga–Ural region: a) the surface of the basement (according to the data of [9, 8, 11, 39]), b) the Paleozoic structural stage (according to the data [5, 6, 8, 11, 13, 34, 39]), c) the modern erosion surface (the scheme of identifying the digital map of the relief). *1*—isohypses of the basement roof (a) and the Vereiskian horizon (b); *2*—the Riphean aulacogens; *3*, *4*—the axes of the swells (3) and the minor folds (4); *5a*—the major fractures, *5b*–the minor fractures; *6*—upthrows–overthrusts; *7*—normal faults; *8*—fractures in the scheme (*c*). Zones of dislocations: SKZ—Sura–Kama; ZhZ—Zhigulev; Rhipean aulacogens: KBA—Kama–Belskii, SAA—Sernovodsk–Abdulin; TKA—the Tokmov arch and its apices: Na—Nizhniy Novgorod, Sa—Sundyr, Ka—Kanash, Ua—Ulyanovsk, Ta is Tokmov; the scarps: NTS—Northern Tatar, STS—Southern Tatar; depressions: KKT—the Kazan–Kazhim trough, MD—the Melekess depressions; local structures mentioned in the work: Ks—Karlin, Ts—Tetyushi, and Us—Ulemin (swell)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54°
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Sa
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Volga R.
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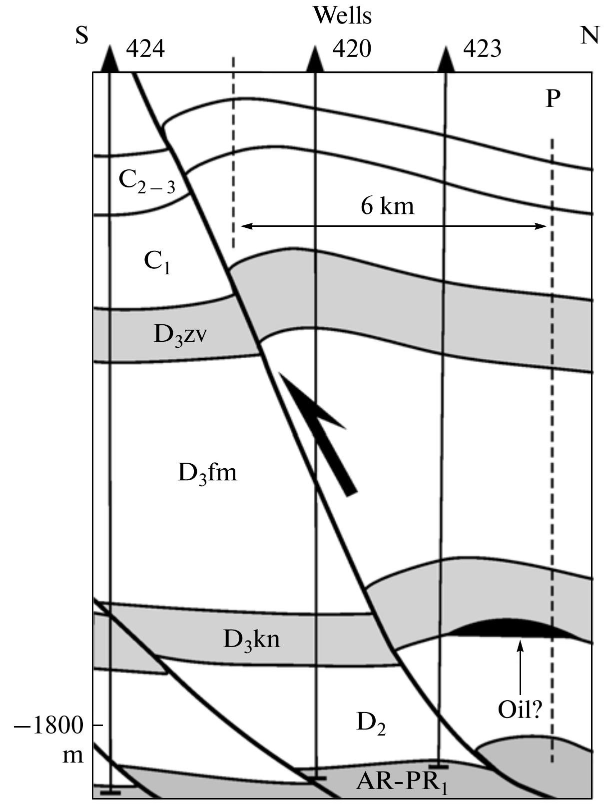


Fig. 2. Scheme of one of the Ulemin swell structures related to the listric upthrow–overthrust (the location is indicated in Fig. 3a), according to [34]

placements that have elements of overthrust, strike-slip, and rotation [34]. Taking the asymmetric structure of the swells into account, the phenomenon of the migration of the arches is explained by the development of listric upthrows–overthrusts under horizontal compression [13, 14, 34].

Another feature of the swells located in the SKZ is the undulation of their apices, which causes the disintegration of the linear structure of a swell into chains of small brachiform folds. An analysis of the detailed structural maps of different horizons in the cover [4, 34] allows correlation of these features with the occurrence of several folding phases. NE-striking swells are frequently found within the SKZ and its margins, and NW-extending and meridional structures occur less often. The position of the systems of "minor" folds [6, 8] also indicates the existence of at least two folding phases that are spatially bounded to the fracture structures of the SKZ (Fig. 1b).

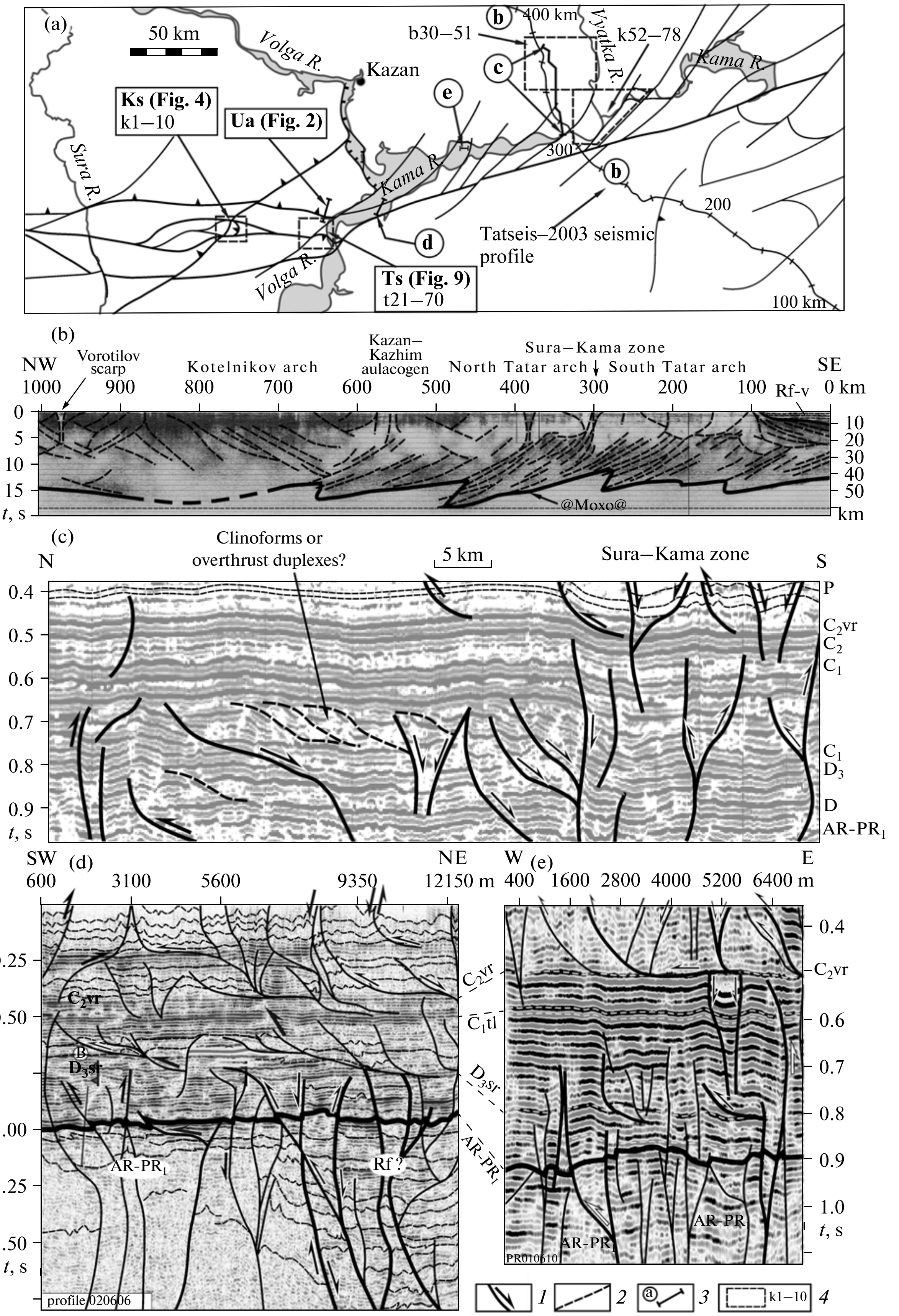
Geophysical data conform to the features of the SKZ tectonics. Its shape is emphasized by the chains of magnetic anomalies located en echelon and linearly in its central segments and fan-shaped at the flanks. With respect to adjacent blocks, the SKZ is characterized by low values of the force of gravity and even smaller velocities of the longitudinal waves (5400 m/s) in the basement rocks, which is explained by their tectonic disintegration [37].

The seismic image of the crust along the Tatseis geotraverse crossing the SKZ within 295–330 km makes it possible to assume that at the upper crust level (0–15 km) this structure is represented by a strongly compressed synform formed by a series of tectonic plates (Fig. 3a, b) [9]. The seismically foliated lower crust is characterized by an anomalous thickness in the SKZ region and adjacent protrusions of the Tatar arch (Fig. 3b). In this case, its roof and bottom (the Moho discontinuity) have an asymmetric stepwise morphology of a drag fold type. One of the largest lower-crust scarps is projected to the surface in the SKZ region. The inclined reflectors of the lower crust are interpreted as listric upthrows–overthrusts with a dominant displacement in the southeast direction [37]. These features show that the lower crust of this region was crushed and clustered, perhaps due to the outflow of masses from adjacent regions.

At the level of sedimentary cover, the structure of the SKZ is characterized by seismic profiles located on the right bank of the Kama River and in the water area of the Kuibyshev reservoir (Fig. 3) [4, 38]. They show tectonic faults of different types, including upthrows, overthrusts, and normal faults, as well as grabens, folds, and flexures (Fig. 3 c–e). The fractures form complex branched structures and often have a listric and stepwise morphology as well as variable inclinations of the fault planes. The fabrics of the fault systems change in a vertical direction: steeply dipping fractures are overbuilt by the "flower" structures up along the section, which change to shallow stepwise fall and overthrusts of the overlying layers. Here, no faults are through; they are all blind and rootless. In the section, there is also disharmonic alternation of the packages with horizontally foliated and fracture-folded structures (Fig. 3d–e). The seismic image of the latter is shown in the partial loss of in-phase axes, but the folds are identified and confirmed in surface observations (see below). These features can be explained by the continuous polystage development of the SKZ, which determined the structural unconformity and disharmony of the cover layers; however, another interpretation is also possible (see below).

We consider the structural features of the western, central, and eastern segments of the SKZ based on the

Fig. 3. Seismic profiles crossing the Sura–Kama zone: (a) the scheme of location of profiles and segments of detailed works; (b) the Tatseis–2003 seismic CDP profile (according to [37]); (c–e) the local seismic profiles: (c) the area of the Vyatka river mouth [38], (d–e) the water area of the Kuibyshev Reservoir [4] (the location is indicated in Fig. 3a). *1*—the fractures and orientations of the displacements; *2*—the seismic reflections; *3*—the location of the profiles in the scheme (a); *4*—the segments of detailed works and the numbers of the observation points


(a)
50 km
Volga R.
Kazan
b30–51
k52–78
400 km
Vyatka R.
Kama R.
Ks (Fig. 4)
k1–10
Ua (Fig. 2)
Sura R.
Kama R.
300
200
Tatseis–2003 seismic profile
Volga R.
Ts (Fig. 9)
t21–70
100 km
(b)
Vorotilov scarp
Kotelnikov arch
Kazan–Kazhim aulacogen
Sura–Kama zone
North Tatar arch
South Tatar arch
NW
SE
Rf-v
@Moxo@
t, s
km
(c)
Clinoforms or overthrust duplexes?
5 km
Sura–Kama zone
N
S
P
C2vr
C2
C1
C1
D3
D
AR-PR1
t, s
SW (d)
NE
600 3100 5600 9350 12150 m
C2vr
C1tl
D3sr
AR-PR1
Rf ?
profile 020606
W (e)
E
400 1600 2800 4000 5200 6400 m
C2vr
AR-PR
PR010610
t, s
1
2
3
4
k1–10

example of several key areas known as Karlin, Tetyushin and Lower Kama dislocations.

TECTONICS OF THE KARLIN STRUCTURE OF THE STRIKE-SLIP DUPLEX

The Karlin structure (KS) is located in the western segment of the SKZ in the basin of the Karla River, the left tributary of the Sviyaga River (Fig. 1). It has been attracting the attention of researchers for a long time as a unique system of high-amplitude fold—overthrust dislocations developed in the Paleozoic and Mesozoic deposits. Contributions to the history of its studies were made by A.P. Pavlov, A.V. Nechaev, E.V. Milanovskii, G.I. Blom, V.V. Bronguleev, A.K. Krylova, R.N. Valeev, A.P. Kapustin, Yu.G. Semakin, M.L. Rudnev, and many other geologists [5, 6, 8, 11, 29, 33]. The dual nature of the KS, featuring a linear and a ring structure, has generated many discussions. Currently the KS structure has been most fully presented in models of its coptogenic [28, 41] and tectonic origin [8, 11, 33].

As a result of our structural studies we established that the KS is confined to the central part of one of the strike-slip duplexes in the western segment of the SKZ (Fig. 4, the inset). In its structure, there are isolated structural parageneses of two main generations that correspond to two stages of deformation: 1) early strike-slip overthrust transpressional and 2) later transtensional structures.

Structural Parageneses of the First Stage of Deformations (D_1)

Earlier structural parageneses are represented by a system of fold—overthrust nappe and shear faults. The formation of the nappe—overthrust structures was controlled by strike-slip faults confining the nappe along the southern and northern flanks of the KS. As a result, the current surface within a large area of weakly dislocated Jurassic and Cretaceous deposits has formed a structure of the "Napoleon's tricorn" type about 10 km in size (Fig. 4). It is composed of the Upper Permian carbonate (Kazan stage) and carbonate terrigeneous (Tatarian stage) deposits that are thrusted over Middle Jurassic—Early Cretaceous sandy—clayey and limestone layers. Multiple doubling and recumbence of the fragments of this section were revealed in the outcrops and in drilling; in the imbricated allochthonous plates, lying and plunging overlapped folds were encountered [5, 6, 8, 11, 33].

At the eastern frontal segment of the KS, fold—overthrust faults are mostly flat dipping faults (Fig. 5, sections I—II, I—III). Here, the overlapped folds and the overthrust zones are secondarily "imbricated" and crumpled into recumbent folds, which reflects the processes of clustering and crushing of tectonic packages in the allochthonous front. The root region of the nappes is located in the western segment of the KS, which is controlled by the steeply dipping system of dislocations of the NE-striking Endugan fault (Fig. 4). In the NE and SW directions from the KS, the amplitudes of visible vertical displacements of this fracture sharply decrease. In the western segment of the KS, the Endugan fault is represented by the system of recumbent folds, normal faults, upthrows, and upthrust—overthrusts with a strike-slip component of displacements (Figs. 4, 5). These fractures are linear and arc-shaped, and the degree of their curvature increases in an eastern direction, which is probably related to the consecutive renewal of the Endugan fault during and after the formation of the nappe structures.

The internal structure of the tectonic plates is characterized by intense plastic and brittle strains that caused the development of the zones of brecciation, boudinage, and foliation of rocks, boudinage structures, overthrust duplexes, and minor asymmetric folds (Fig. 6a). Along the overthrust surfaces there are mylonites and clay gouges with striations. At the base of the tectonic plates and mainly in the frontal part of the nappes, there are widely developed zones of tectonic melange with a thickness of up to the first tens of meters. They consist of groundmass and fragmentary inclusions with a size ranging from the first centimeters to several meters, represented by the rocks of the Upper Permian—Upper Jurassic stratigraphic interval [33]. There are angulated lumps and small fragments, lens-shaped bodies that sometimes are crushed into drag folds and form "snow ball" structures (Fig. 6b).

The flat nappe—overthrust structures of the frontal segments of the KS gradually change to more steeply dipping faults on drawing near to the root part of the nappes in the area of the Endugan fault. The similar situation is recorded along the northern and southern flanks of the KS confined by the strike-slip faults until the occurrence of subvertical fractures (Fig. 5). Steeply dipping tectonic plates mainly of shear slip are often encountered here (Fig. 6c).

The statistical analysis of elements of the occurrence of sedimentary layers within the KS allowed us to identify three generations of folds. In the stereogram poles of foliation are located along the three main belts occupying the trajectories, in the first case along the arc of the big circle (cylindrical folds F_1) and in the other two cases, in respect to the arcs of the small circles (the conical folds F_2 and F_3) (Fig. 7a). The first two systems of folds (F_1 and F_2) have an almost identical NNE and NE orientation of their axial planes and are characterized as asymmetric structures of the SE and ESE vergence. In view of the fact that these folds are almost coaxial and reflect the tendency of change in the morphology from cylindrical to conical (pull-apart) structures, we may expect that they are connected with a single stage of progressive development of right-lateral strike-slip dislocations (D_1), which caused the structures to rotate clockwise. The stereogram also reconstructs flat conical NW-striking folds, as well as the subisometric field of scattering of poles of foliation characterizing the domed

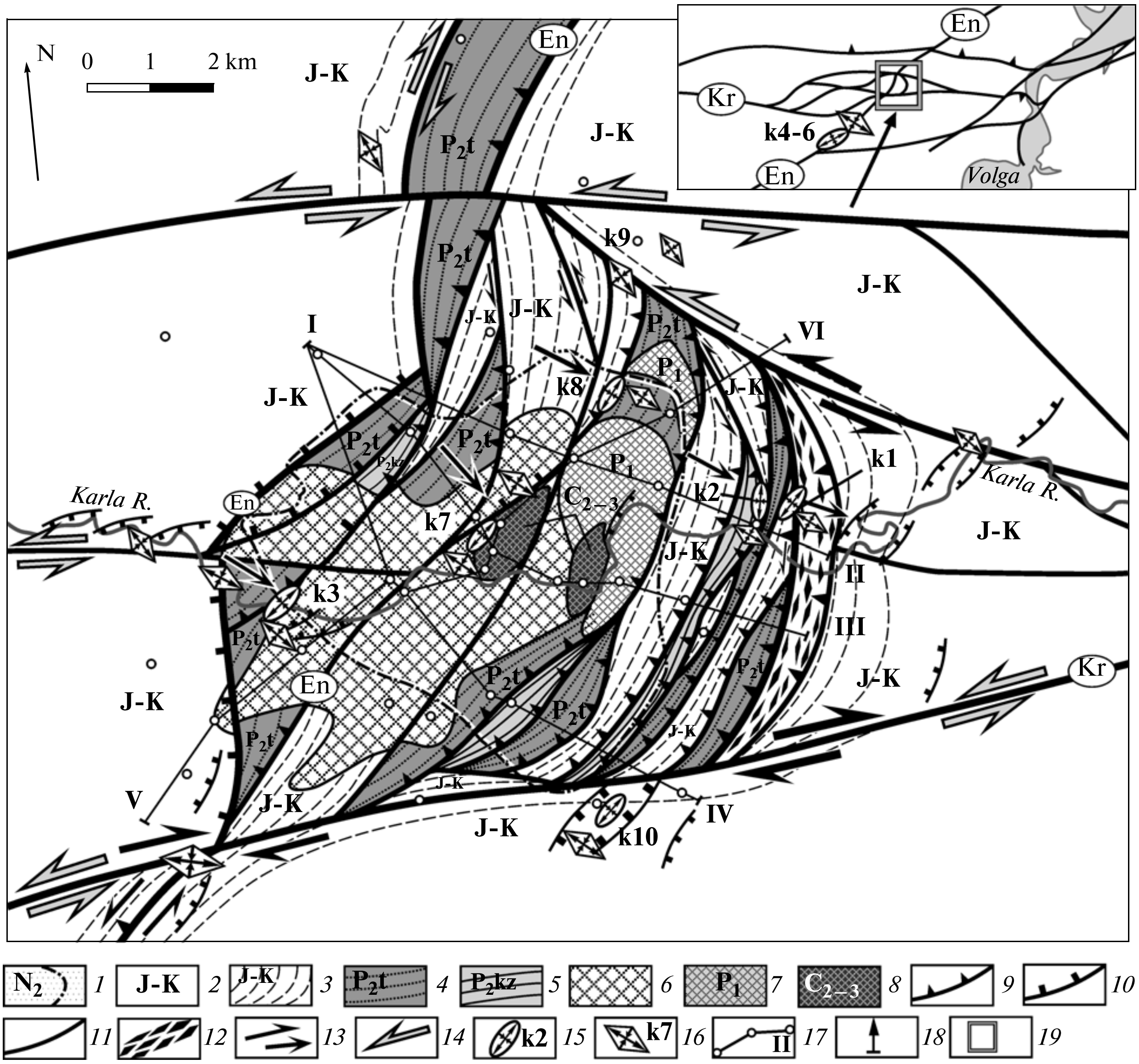


Fig. 4. Structural scheme of the Karlin structure (the geological basis according to [11, 33]). The location is presented in the inset and Fig. 1. *1–5* are deposits: *1*—the Pliocene (at the sections of Fig. 5) and the contours of their occurrence (Fig. 4), *2*—weakly dislocated Jurassic–Cretaceous, *3*—fold Jurassic–Cretaceous, *4*, *5*—Upper Permian of the Tatar and the Kazan stages, respectively; *6–8*—tectonized carbonate rocks of the protrusions: 6—mixtite-like brecchias, *7* of the Lower Permian, *8* of the Middle and Upper Carboniferous; *9–11*—fractures: *9*—upthrows and overthrusts; *10*—normal faults; *11*—strike-slip faults; *12*—the melange zone; *13*, *14*—the orientations of displacements: *13*–early (D_1) and *14*—late (D_2) stages of deformation; *15*, *16*—the numbers of the stakes and the established subhorizontal position of the principal axes of strains: *15*—the early (D_1) and *16*—the late (D_2) stages; *17*—the lines of the drilling profiles; *18*—the wells (at the sections of Fig. 5); *19*—the contours of the segment in the inset. The faults: En is Endugan and Kr is Karlin.

structures that are considered tectonic formations of the second stage of deformations (D_2) (Fig. 7a) (below).

Structural and kinematic studies within the KS were carried out based on the studies of slickensides, ruptures, asymmetric minor folds, boudines, rotational structures, and displacements along the fractures. The observations covered almost all rock complexes forming the KS for which kinematically identical structural parageneses were revealed. The statistical analysis of the displacement vectors along the faults made it possible to identify two major structural–kinematic parageneses (Fig. 7b–h). The first of them corresponds to early overthrust nappe and strike-slip structures of the stage D_1. For the upthrows and overthrusts of this paragenesis that often have a strike-slip component, displacements in the E–SE and SE directions are reconstructed (Fig. 7 b–d, g). They are kinematically consistent with the right-lateral strike-slip faults of sublatitudinal strike (7b, h), as well as left-lateral transpression faults of the NNE striking Endugan fault (7e). The positions

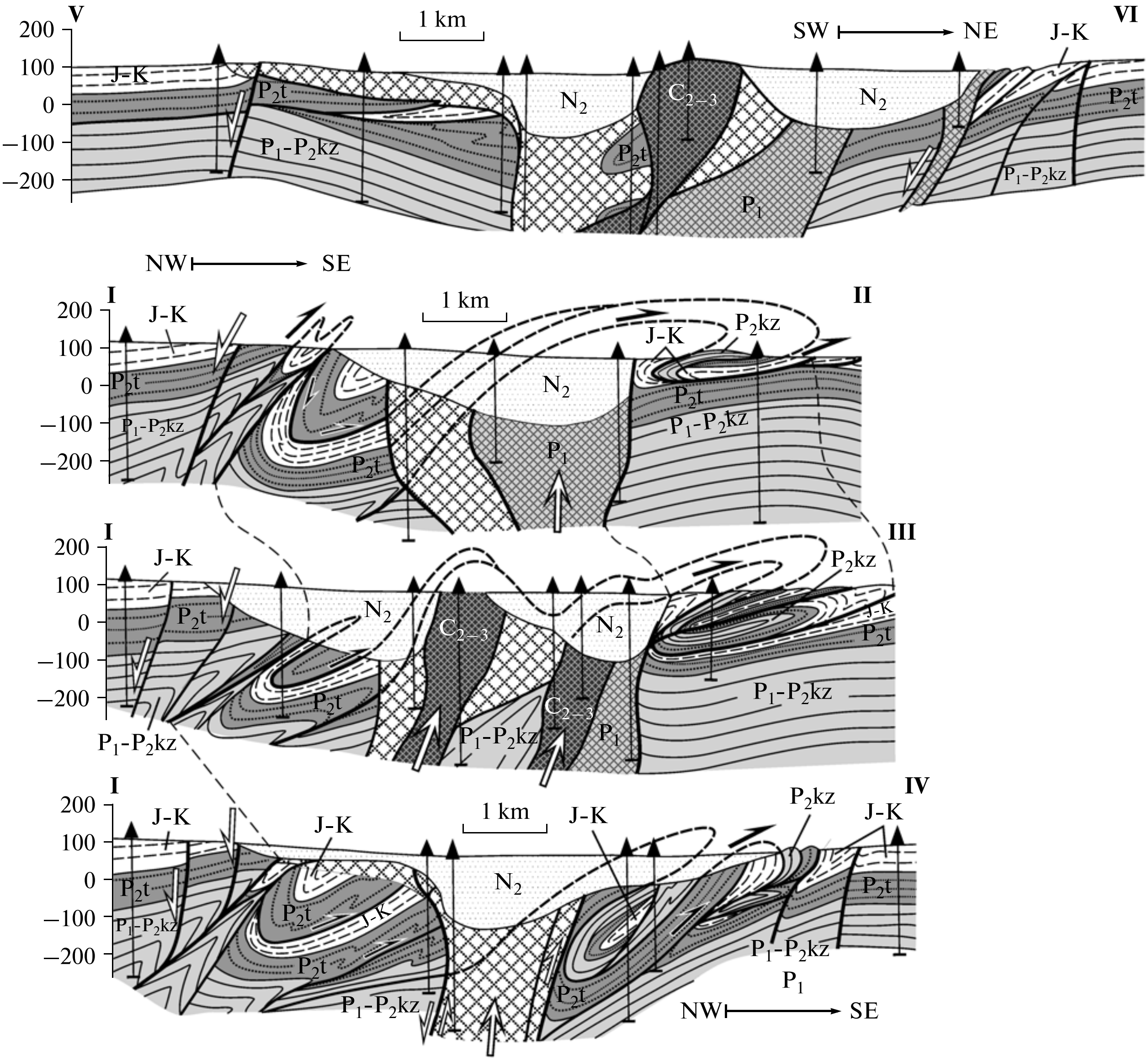


Fig. 5. Geological and structural sections of the Karlin structure (geological basis according to [33]). The location of the drilling profiles and the description are given in Fig. 4.

of the compression axes obtained using the FaultKin6 software for this structural paragenesis mainly conforms to the NW–SE horizontal direction. This is consistent with the field of paleostresses identified based on the analysis of the folded structures (Fig. 7a, 7b–e, g, h). The orientations of the principal strain axes are shown in the structural map at the respective points of observations, which enables us to determine fault kinematics at the early stage of deformations (Fig. 4). In general we note that at this stage the KS was formed under transpression. The development of the overthrusts and nappes was associated with the right-lateral strike-slip displacements along the sublatitudinal zone forming the southern flank of the structure. The northern flank of the KS and the protrusion of the nappes towards the SE were controlled by the NW-striking left-lateral strike-slip faults.

Structural Parageneses of the Second Stage of Deformations (D_2)

The later structural parageneses are represented by the system of normal faults, falls, transtentional faults, and strike-slip faults, as well as bunch-shaped and dyke-shaped injection bodies of strongly disintegrated carbonate rocks: tectonites representing a stratigraphic interval of deposits from the Middle Carboniferous to the Upper Permian. A significant amount of these teotonites were transformed into carbonate "flour" consisting of the fragments and blocks of rela-

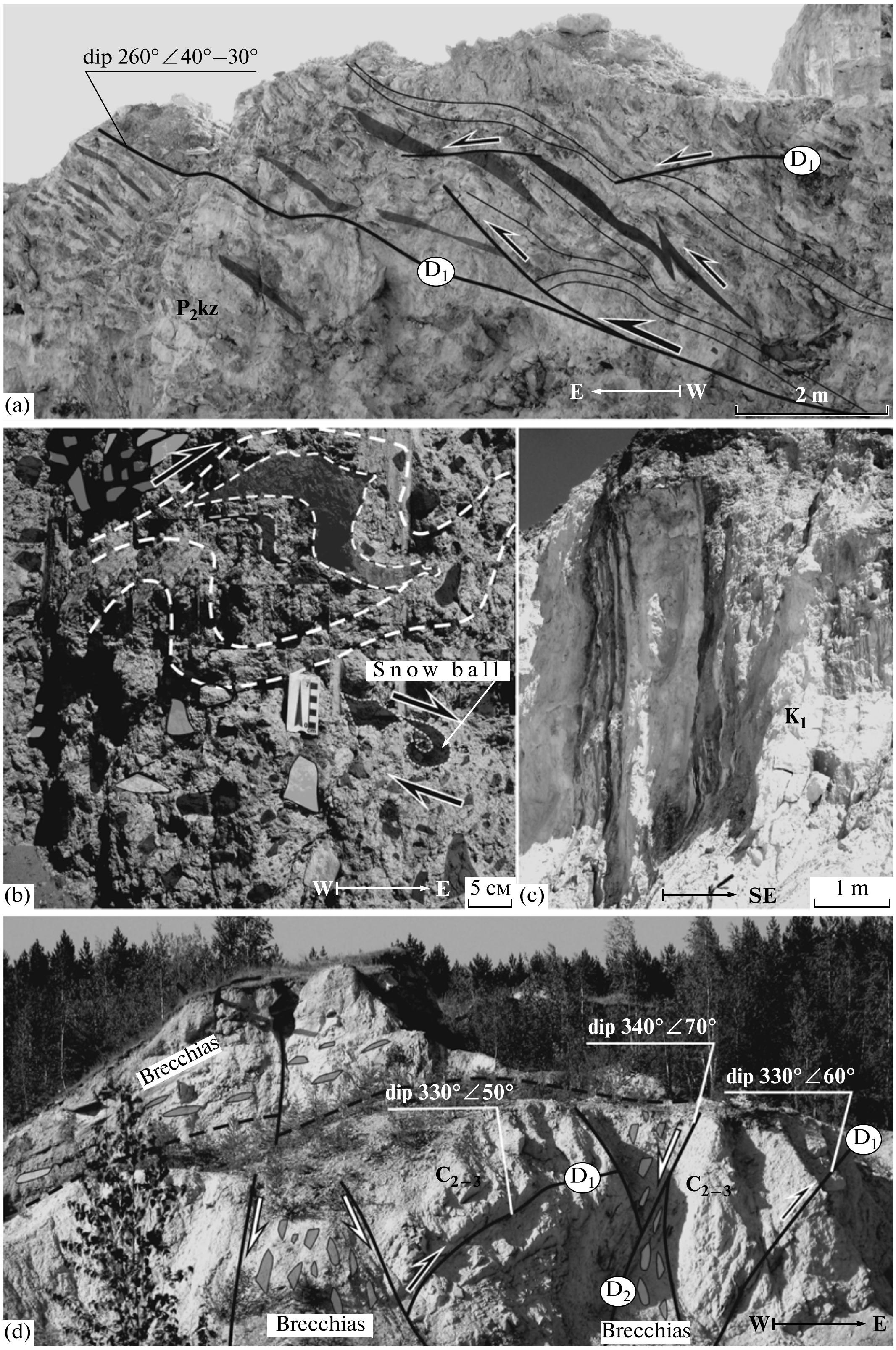


Fig. 6. Photos of the structures of the dislocated rocks from the Karlin structure (the sectional view): the early overthrust dislocations (D_1) in (a) the allochtonous plate of the Kazan stage, (b) in the melange zone; (c) the tectonic plates with transpressional displacements in the Lower Cretaceous deposits; (d) the systems of faults in the area of vertical protrusions. The explanations are given in the text.

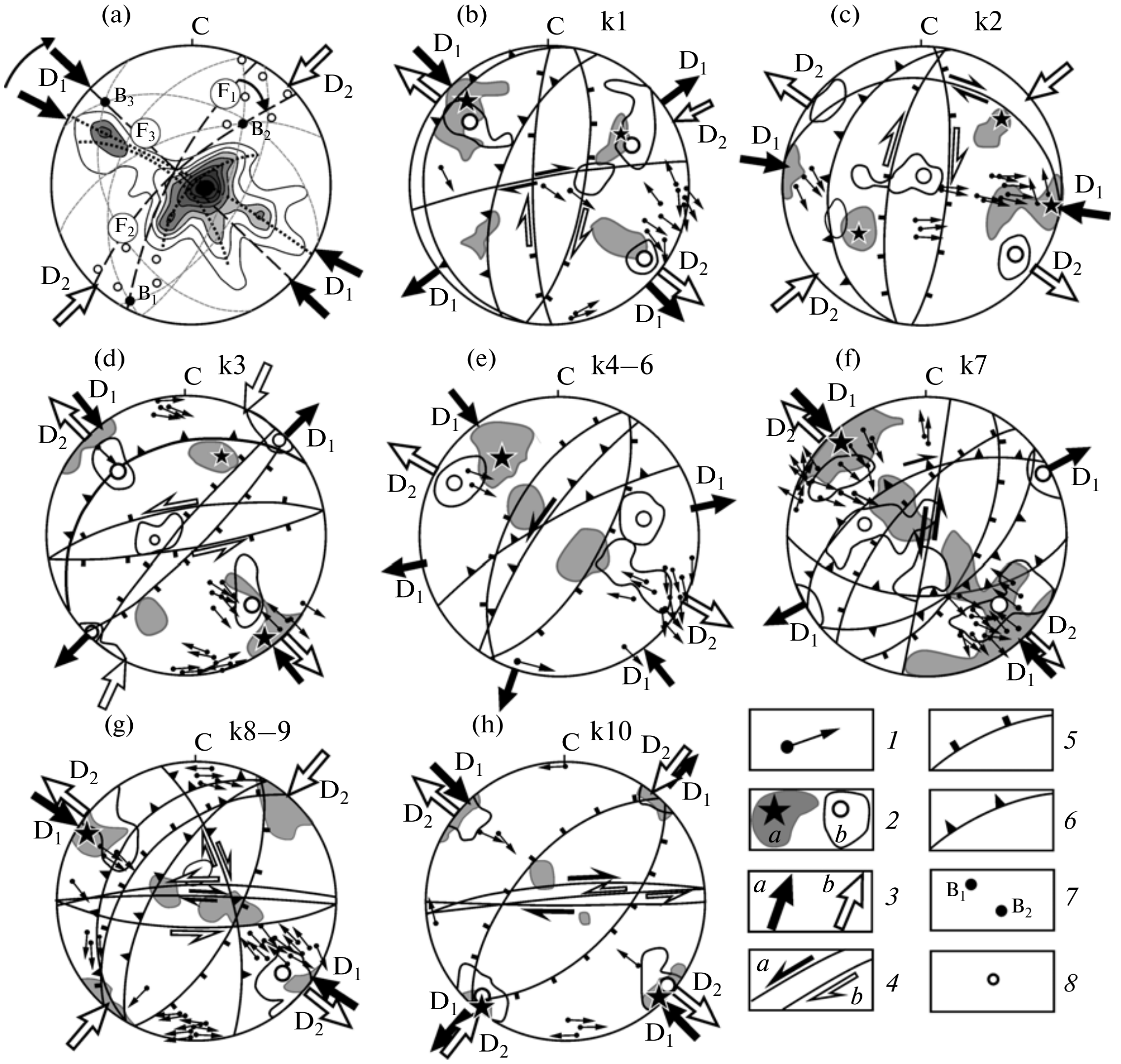


Fig. 7. Stereographic projections (the lower hemisphere): a—the foliation poles in the Karlin structure (n = 226, isolines: 1, 2, 4, 5, 6, 8, 9, and 10%); b–h—the poles of shears and separations from displacement vectors of the upper limb: b–stake k1 in the melange zone; in the Upper Permian deposits: c—stake k2, d—stake k3; e—stakes k4–6 in the Jurassic deposits (shown in the inset); f–stake k7 in the region of protrusions in carboniferous limestones; g–stakes k8 and 9 in the Mesozoic and Upper Permian deposits; h–stake k10 in the Mesozoic deposits. The location of the stakes is shown in Fig. 4. *1*—the poles of faults and displacement vectors of the upper limb; *2*—the position of the principal axes of strain and the areas of their dissipation: a—compression, b—extension; *3*—the projections of the principal axes of strain on the horizontal plane: *a*—early (D_1) and *b*—late (D_2) stages; *4*, *5*–the averaged positions of the fault planes: *4*—strike-slip faults, of early (*a*) and late (*b*) origin, *5*—normal faults, *6*—upthrows and overthrusts; *7*, *8*—the apices of the folds (B_1, B_2, and B_3) obtained geometrically (*7*) and by the measurements in the outcrops (*8*). F_1, F_2, F_3—the axial planes of folds of different origin.

tively monolithic, but strongly disintegrated limestones with sizes ranging from several centimeters to many tens of meters. The sizes of the injection carbonate bodies vary from a few hundreds to many hundreds of meters. The biggest bodies (0.5–2.5 km) form a series of vertical protrusion that break each other and the system of overthrusts–nappes in the central segment of the KS (Fig. 5). In the horizontal section, the protrusions form the lens-shaped bodies that linearly extend in the SSE–NNE direction (Fig. 4). The structure of relatively weakly disintegrated blocks of protrusions shows relict fragments of the early overthrusts and upthrows (D_1), as well as later superimposed overthrusts (D_2), whose combination is realized in the lens-shaped and fan-shaped structures of vertical squeezing of substance (Fig. 6d). Thus, we may assume that the protrusions started form at the stage of transpression (D_1), but they have a superimposed character with respect to the earlier structures (D_1) within the observed upper level of the section. The protrusions are closely associated with clastic dykes and minor bunches representing fall cavities filled with fragments of carbonate rocks.

Among the protrusions in the central segment of the KS there are structures of different depth that have been identified by the domination of inclusions of a particular stratigraphic interval in their composition [11, 33]. Along the periphery they are framed by mixtite-like breccias composed of carbonate "flour" and "mixed" fragments of the Middle Carboniferous–Upper Permian carbonate rocks. Sometimes, instead of tectonic flour, the fragmentary inclusions are cemented by travertine-like and skeletal leached carbonate formations, which indicates a high level of tectonite fluidization. At the upper structural level, mixtites often form trails: layers and lenses of redeposited formations containing weakly rounded fragments of limestones and having relatively stable thickness (tens of meters). These formations overlie the Tatarian stage and Mesozoic rocks with nonconformity and shape boudins containing small fragments of Miocene rocks that are absent in the root sections of this territory [28]. Based on this, the age of mixtite-like brecchias is estimated as Miocene [11, 33], but taking into account the fact that these formations are partly redeposited, the Miocene should be considered as the upper age threshold of their formation.

The trails of the redeposited brecchias have isolated structures of horizontal flow and foliation, as well as minor asymmetric creep folds, whose vergence indicates centrifugal directions of displacement of substance relative to the protrusions in the central segment of the KS. According to the results of drilling, the platy structures (boudinage and foliation) of mixtite-like brecchias are characterized by a flat (5°–30°) occurrence of protrusions in the surface layers. The situation gradually changes down the section at the depths of 100–450 m where the structures lie steeply and subvertically. At depths greater than 450 m elements of flat tectonic foliation are encountered again. Thus, the roots of the protrusions are confined to the surface of fall and the subhorizontal flow of substance at the level of Middle Carboniferous (the Vereiskian horizon?), above is the zone of subvertical squeezing that changes to the region of gravitational flow of the material over the ancient erosion surface [33].

The protrusions of the central segment of the KS form a subisometric rise, 2003 km wide, which is framed by a ring depression up to 5 km in diameter filled with Lower Pliocene lake deposits up to 250 km thick. The base of their section shows a sharp angular displacement and sandy–gravel layers. At the slopes of the central rise formed by the protrusions in these layers, there are features of gravity sliding, lenses and erratic masses of Paleozoic and Mesozoic rocks, which makes it possible to consider them olistostrome [33].

In general, the considered structural and material paragenenes unites the normal faults and strike-slip faults, injection structures and upper levels of vertical protrusions, related forms of surface flow of substance, mixtite-like brecchias, as well as the paleomorphic structures of the central rise and the ring depression filled with the Pliocene sediments. Thus the combination of the structures and the tectonites can be explained by the models of the impact event [28, 41] and the ideas about the development of the injection structures at the intersection node of fractures [8, 11, 33].

Structural–kinematic data point to the tectonic origin of the second generation structure. The main elements of this paragenesis are the structures of subhorizontal extension: the conjugated normal faults with a different inclination of fault planes, related mesostructural fault ridges and grabens, transtensional faults and strike slips, ruptures, and fall cavities that are often represented as clastic dykes and lens-shaped stocks. In general, these faults strike NNE and NE, which indicates the subconformal character of their propagation in respect of the fold–overthrust structures of the first generation (Fig. 7b–h). Here, the outcrops exhibit steeper deposits and imposed-crossing relations between normal fault planes (D_2) and the earlier overthrust structures (D_1) (Fig. 6d). The sublatitudinal left-lateral strike-slip faults that are dynamically conjugated with the normal fault systems show the features of kinematic inversion in respect of sublatitudinal right-lateral strike-slips of the first generation (Fig. 7d, g-h). An inversion of strike-slip displacements is sometimes recorded within the single zones that have isolated shears with left- and right-lateral displacements.

The late structures (D_2) under consideration penetrate all complexes of the KS Paleozoic and Mesozoic rocks. Sometimes normal faults of this system with minor amplitudes of displacements also penetrate the lower horizons of the Pliocene deposits of the ring depression, but they attenuate up along the section. In the structure of protrusions of the KS central segments, the normal faults (D_2) have complex relations with divergent systems of steeply dipping upthrows (D_1) (Fig. 7f). The spatial combinations of both structures, in fact, reflect a single process of vertical uplift of carbonate rocks to the surface. This may indicate a continuous development of protrusions at the early (D_1) and late (D_2) stages of deformations

The kinematic data show that at the second stage of deformations the structural parageneses developed mainly under left-lateral strike-slip transtension and subhorizontal NW–SE extension, which reflects the situation of the full kinematic inversion that occurred during the transition from the early to the late stage of KS development (Fig. 7). The linear–tranverse character of the location and orientation of the structures (and paleostresses) of the second generation does not conform with the radially concentric structure that is theoretically expected for an impact event. Its elements are partly typical of the ring depression and folds of gravity sliding, whose complex is explained by compensatory downwarping related to the formation of vertical protrusions and landslide phenomena on the slopes of uplifts.

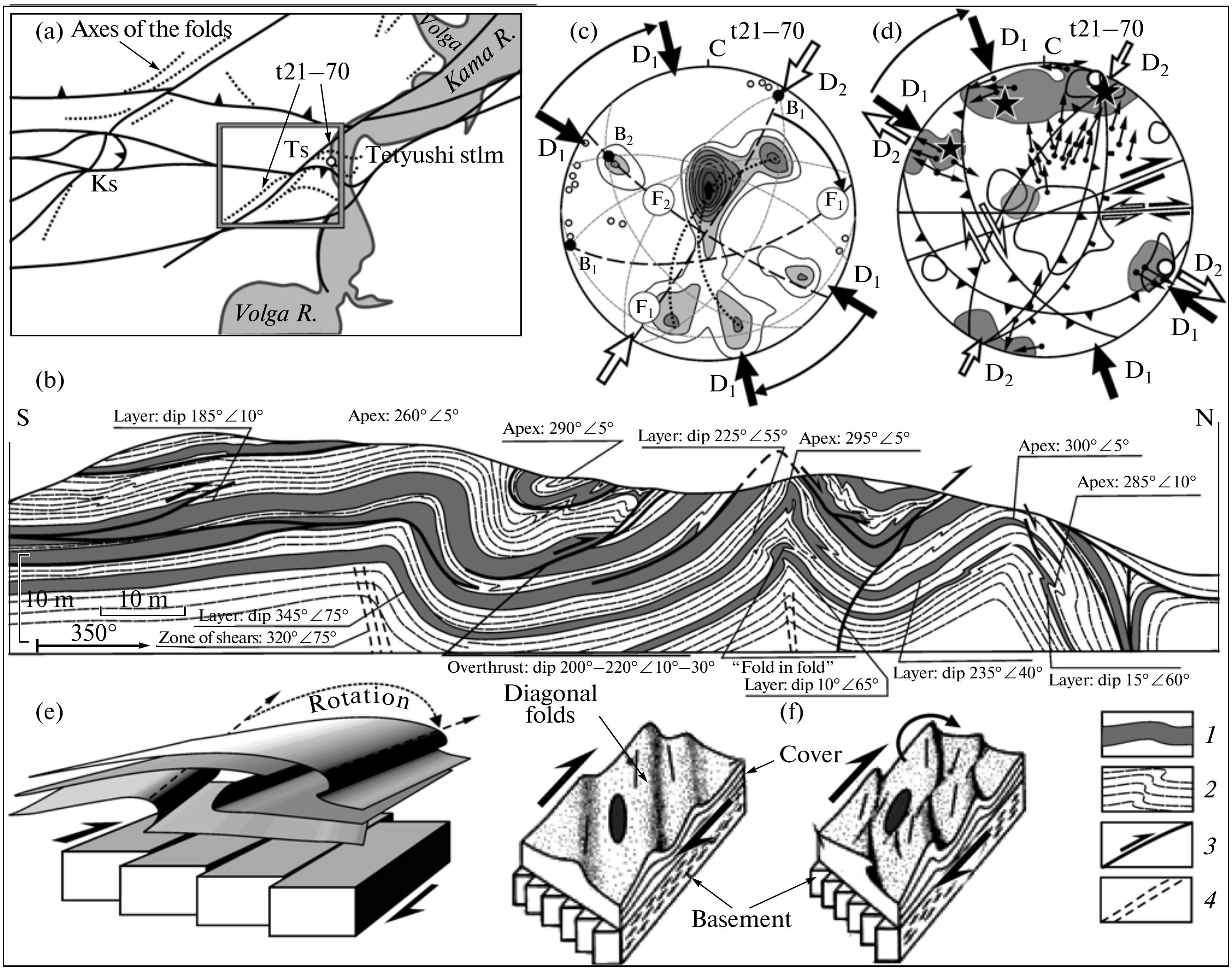


Fig. 8. Schemes illustrating the structure of fold dislocations in the Tetyushi region: a—the location and contours of the section of the detailed works, b—the geological–structural section of dislocated deposits of the Tatarian stage (the pier in the Tetyushi settlement); c, d—the stereographic projections of the structural elements of the Permian and Mesozoic deposits within the segment of the detailed works and stakes t21–70 (the lower hemisphere): c—of the foliation poles ($n = 178$, the isolines: 1, 3, 4, 6, 7, 8, 10, and 11%), d—of the poles of shear and separations from displacement vectors of the upper limb (the conventional signs are given in Fig. 7); e—schematic construction diagram of the Tetyushi rotation folds related to the deep strike–slip zone; f—diagrams illustrating the mechanism of the formation of diagonal and rotation folds in the plastic cover due to the simple shear strain in the basement according to [42]. *1*—limestones; *2*—argillites and marls; *3*—fractures and displacements along them; *4*—shears.

TECTONICS OF THE TETYUSHI FOLD STRUCTURE

The Tetyushi structure (TS) is confined to the central segment of the Sura–Kama zone (SKZ) where it crosses the valley of the Volga River and slightly bends, changing the strike from latitudinal to the ENE (Fig. 1). The TS folds are exposed in the scarps of the right bank of the Volga River in the area of the Tetyushi settlement located at 60 km east of the Karlin structure (Fig. 8a, b). This system of folds covers a vast area and can also be observed in the basin of the upper reaches of the Ulemy River 10–15 km west of the Tetyushi section (Fig. 8a). The fold axes within this segment change their SW–NE orientation to the NW–SE. Their apices orient variously also in the separate outcrops. The dislocations are composed of Upper Permian and Jurassic deposits.

The fold structures in the area of the Tetyushi settlement are complicated by red beds of the Tatarian stage and are exposed in a band up to 200 m wide (Figs. 8b, 9a). They gradually flatten and change to the area where the strata dip flat and are complicated by the zones of substratum fall and tectonic flow. The latter ones expose R-shears, asymmetric boudines and minor disharmonic folds associated with the development of stratum falls and overthrusts (Fig. 9b). The folds change their morphological features even within one single structure, showing the consecutive stages of its development from a relatively ordinary asymmetric fold to a recumbent one, and later on a disharmonic lying fold of plastic flow (Fig. 9b). Figure 9b shows a

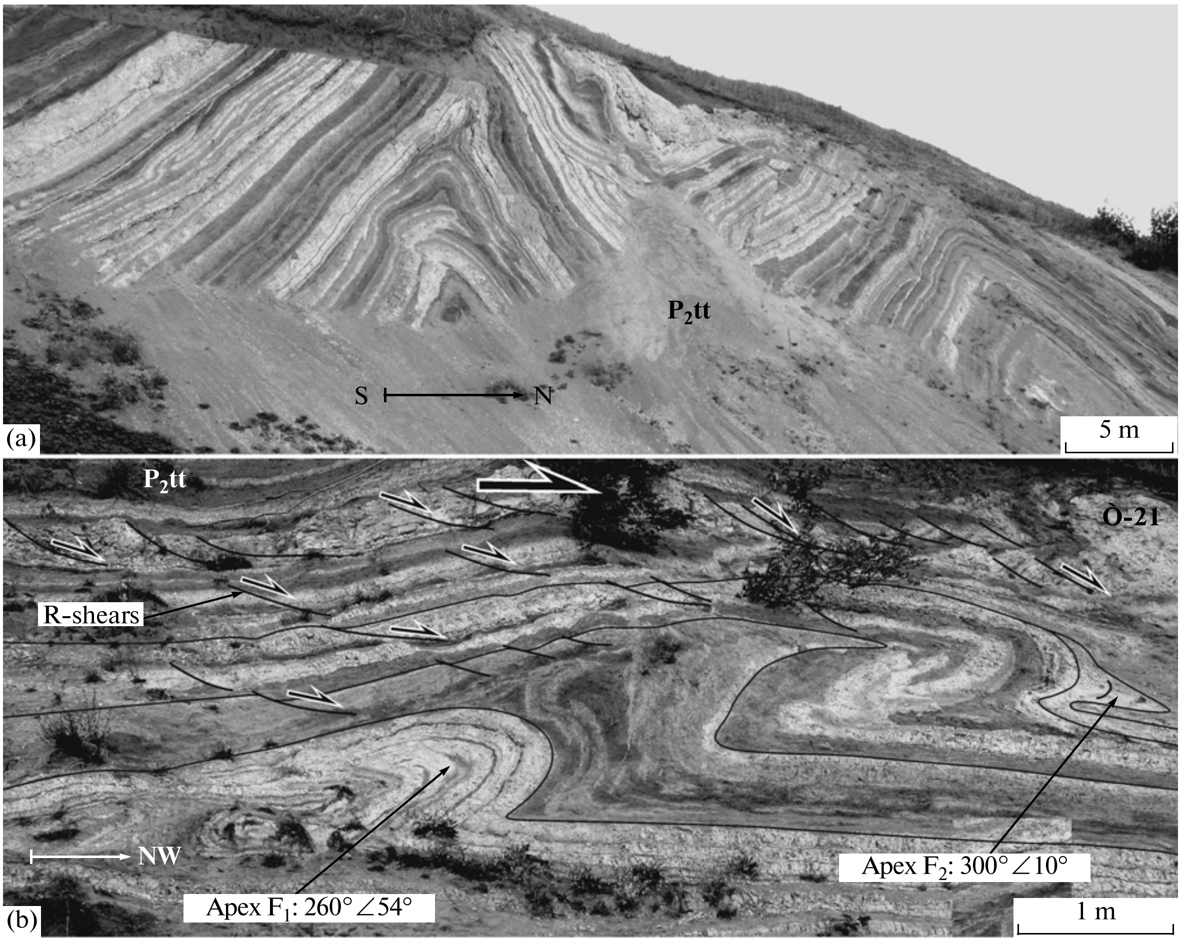


Fig. 9. Photos of the Tetyushi folded structures in the deposits of the Tatarian stage: a is the major folded structures in the area of the pier in the Tetyushi settlement, b is the minor asymmetric rotation folds of the substratum flow east of the Tetyushi settlement. (The symbols are explained in Fig. 7).

frequent gradual change in the orientation of the apices of the folds accompanied by their rotation around a vertical axis at an angle up to 40°. The volume reconstruction of this situation is presented in the diagram (Fig. 8e).

In the northward direction the region of flat zones of substrata flow changes to the system of major folds (around the pier in the Tetyushi settlement) that crumple these zones (Fig. 8b). These structures are characterized as asymmetric inclined folds with vergence in the northern rhumbs that, based upon regional data, change to counter vergence of the structures in the northern flank of the NKZ (Figs. 8a, 2, 3d). The folds have an amplitude of up to 30 m and an upper limb length of 30–60 m. Morphologically, these structures are similar to minor folds of substrata flow in many respects (Figs. 8b, 9b). The principle of similarity of different-rank structures is also observed in the gradual change in the orientation of apices of the both folds: Figure 8b shows a consecutive change in the position of the apices of large structures from 260° to 300° along the section line from the south to the north. We may consider that these folds are also associated with the flat fall and overthrust zone that is located lower along the section. This version is confirmed by seismic profiling data showing that at the basement of this folded strata package at depths corresponding to 0.25c there is a package of horizontally stratified formations complicated by substrata flow (Fig. 3d).

Statistical analysis of elements of occurrence of sedimentary strata in the area of the Tetyushi settlement and the Ulema River made it possible to identify three generations of the folds. The foliation poles in the stereogram are found along the three major belts occupying the trajectories of arcs of great (cylindrical folds) and minor circles (conical folds) (Fig. 8c). The first two systems of folds (F_1) are characterized as asymmetric structures with NW and NNW vergence, their axial planes strike NE and ENE. In respect of the sublatitudinal strike of NKZ, these structures can be considered as diagonal folds of the early stage of deformation (D_1) associated with right-lateral strike-slip displacements. The change in their spatial position is probably caused by the processes of progressive development of right-lateral strike-slip displacements accompanied by the corresponding clockwise rotation of the structures (Fig. 8e). The later conical folds (F_2) strike NW and represent diagonal structures of the second stage of deformation (D_2) that were formed during the kinematic inversion and when the left-lateral strike-slip displacements occurring along the NKZ (Fig. 8c).

Structural and kinematic studies revealed mainly overthrust and upthrow, less frequently strike–slip and combined displacements along the differently oriented faults (Fig. 8d). We established two main groups of structural parageneses corresponding to two stages of deformation: 1) early upthrows and overthrusts, as well as conjugated sublatitudinal right-lateral strike–slips formed under horizontal compression in the NW–SE direction (D_1); 2) the later normal faults and sublatitudinal left-lateral strike-slip faults, as well as overthrusts and transpressional faults, whose development was associated with the horizontal extension along the WNW–ESE line and (or) horizontal compression in the NNE–SSW direction (D_2) (Fig. 8d). The variations in the orientation of the principle axis of compression recorded in the stereogram for the early stage of deformation are probably connected with a rotation processes in the fault zone. These kinematic data conform well to the results of the analysis of the fold structures (Fig. 8c, d).

There are no strike-slip faults within the central (Tetyushi) segment of the SKZ. The direct features indicating the regional strike-slip occurrence are the systems of folds that are diagonal in respect of the SKZ strike and the rotations of the structures around the vertical axis. The rotation of the fold apices is probably related to the appearance of steeply dipping strike-slip faults in the lower horizons of the cover and the basement rocks (Fig. 3d). Phenomena of this type are well known [16, 17, 42], and the Tetyushi dislocations can be considered diagonal and rotational fold–overthrust structures of strike-slip genesis (Fig. 8e, f). We may suppose that they were formed during the interaction of three factors: 1) the development of substratum falls and other thrust displacements in northern rhumbs, which underwent "suppression" and crushing before the front of the countervergent structures that determined their folding; 2) the influence of the rotational processes related to "blind" strike-slip faulting in the underlying complexes of rocks; 3) manifestation of kinematic inversion of the SKZ in the process of its transformation from the right- to the left-lateral strike-slip structure.

THE TECTONICS OF THE LOWER KAMA DOMINO STRUCTURE

The Lower Kama structure covers the major part of the eastern segment of the SKZ. The interpretation of the digital map of the relief and the analysis of the magnetic anomalies show that the main fault striking ENE and secondary NE fractures feathering it along the northern flank are isolated in the zone structure (Fig. 1). These diagonal faults are found regularly and cut an echelon system of domains 10–20 km wide in the Upper Permian deposits [11]. The internal structure of the domains is faulted by short cross-strike fractures that cut their NE flanks, forming them as a lopsided pile of domino tiles. The features of this structure are well expressed in the modern relief, primarily in the morphology of the Kama River that forms sharp expansions in the NE-frontal parts of the domains: the "domino tiles" (Fig. 1c).

Large swell-like structures and minor pull-apart folds that in general form a right-lateral vein with respect to the main fault of the SKZ are parallel to the diagonal fractures (Fig. 1b). These structures developed in the cover rocks and the basement cover are recorded in the NE direction at a considerable distance from the SKZ, which creates the linear style of the tectonics of the northern Tatar scarp (Fig. 1a, b).

Structural and kinematic studies in the lower reaches of the Vyatka and the Kama Rivers allowed us to receive mesostructural data on the kinematic features of diagonal faults feathering the main zone of the SKZ. We studied two segments in detail: 1) the right bank of the Kama River at the section of the Sokolinye mountains, in Elabuga city, and 2) the right bank of the Vyatka River at a distance of 20–60 km from its mouth (Fig. 10). The kinematic data obtained for these segments are identical in many respects, with the difference that within the first segment covering the "domino" structures, the mesostructural parageneses conform to the megafabric of the SKZ to a greater extent. In this respect, the structures of the second segment that represent a remote zone of dynamic influence of the SKZ are less informative.

Stereographic projections present kinematic data sorted according to the principle of dynamic conformity (Fig. 10). They point to the presence of two groups of structural parageneses that are in many respects identical in spatial and geometrical parameters, but are different in their kinematic features. The main elements of the paragenesis for the structures of the first stage of deformations (D_1) are upthrows and left-lateral transpressional faults striking northeast, as well as sublatitudinal transtensional faults that in general characterize the environment of horizontal compression in the NW–SE direction (Fig. 10a, c). The paragenesis of the structures of the second stage of deformations (D_2) unites the left-lateral strike-slip faults and NE-oriented transtentional faults, conjugated NW-trending right-lateral strike-slip faults, as well as submeridional faults conforming in general to the environment of the sublatitudinal extension–meridional compression (Fig. 10 b, d). Kinematic data indicate that the first stage of the SKZ deformations conformed to the environment of a right-lateral transpression with the main development of northeast oriented diagonal upthrows, swells, and folds. During the second stage, as a result of kinematic reversion, the SKZ was transformed to a left-lateral strike-slip structure, and northeast-oriented diagonal faults were changed to the left-lateral transtensional faults. The extension structures of this paragenesis sharply dominate over the compression structures, which indicates a transtensional environment.

THE RESULTS OF STUDIES AND TECTONIC MORELS

According to the geological–structural and geophysical data we studied, the Sura–Kama zone (SKZ) is a deep tectonic fault that forms the structural stages of the platform and possibly penetrates the lower crustal levels (Figs. 1, 3). There are signs of an inherited and polystage development from the early stages of formation of continental crust in the Volga–Ural craton ($AR–PR_1$) during the establishment of the basement roof and the subsequent evolution of the Phanerozoic sedimentary basins [6, 9, 11]. The obtained structural–kinematic data make it possible to characterize the latest stages of the SKZ development. All studied segments of the SKZ showed the structural parageneses of two stages of the Cimmerian–Alpian deformation characterizing this as a reciprocal strike-slip zone.

The early stage of the SKZ deformation occurred at the right-lateral strike slip and the dominant development of compression structures (diagonal folds, upthrows, overthrusts, etc.), which indicates a general environment of transpression (Fig. 11a, b). For this stage a lower age threshold is recorded by the development of strike-slip–overthrust structures in the Lower Cretaceous deposits (the Karlin structure); the upper one is not clearly age-related, but is bounded by the surface of nonconformity in the basement of presumably Miocene redeposited breccias associated with the development of the apical segments of the Karlin protrusions. Thus, this is the evidence for the Late Mesozoic–Paleogenic time interval or the Late Cimmerian–Early Alpian tectonic cycle of deformations.

The late stage of the SKZ deformations occurred during the left-lateral strike-slip transtension, which resulted in the formation of mainly the extension structure (transtensional faults, expansions, pull-apart basins, etc.) (Fig. 11a, c). An early age threshold is not clearly specified for this stage. We may state that deformations of this type actively developed in the Pliocene because of the structures of gravity sliding of early Pliocene sediments of the ring depression on the slopes of the Central rise of the Karlin protrusions. Taking into account the fact that certain faults penetrate the Quaternary deposits, and they all are well identified and emphasized by the morphology of the modern relief, we may assume that the deformations of the second stage also continued in the Quaternary. In general, the late transtentional deformations correspond to the late Alpian cycle. The revealed stage

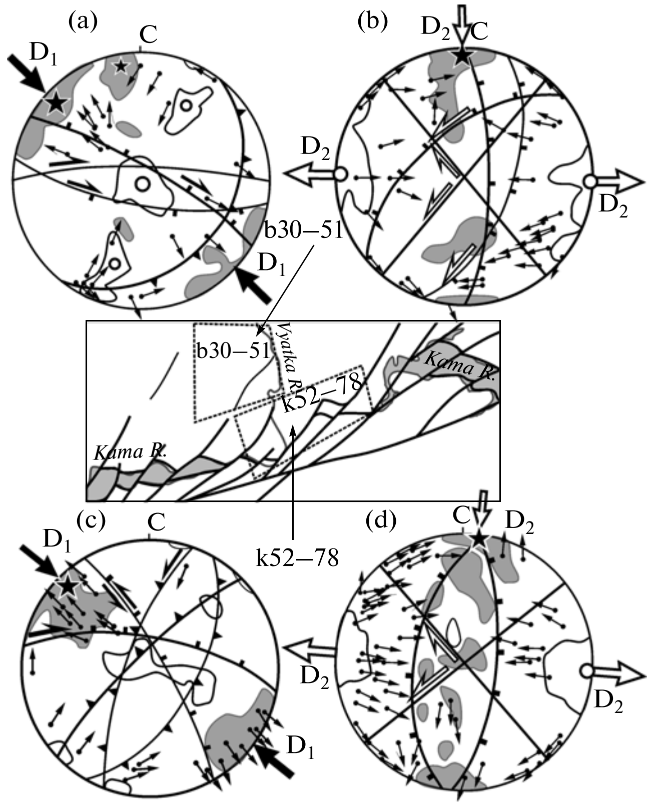


Fig. 10. Strereographic projections (the lower hemisphere) of the poles of shears and fractures in the Upper Permian rocks with displacement vectors of the upper limb for the segments: a, b—the right bank of the Vyatka river at stakes b30–51; c, d—the right bank of the Vyatka river in stakes k52–78 (the location is given in the inset).

character of the SKZ development conforms to the regional facts about the sequence of occurrence of fold–fracture structures in the Volga–Ural province [7, 11, 33, 35].

An interesting feature of the SKZ structure is its inhomogeneity in the vertical and lateral–longitudinal directions.

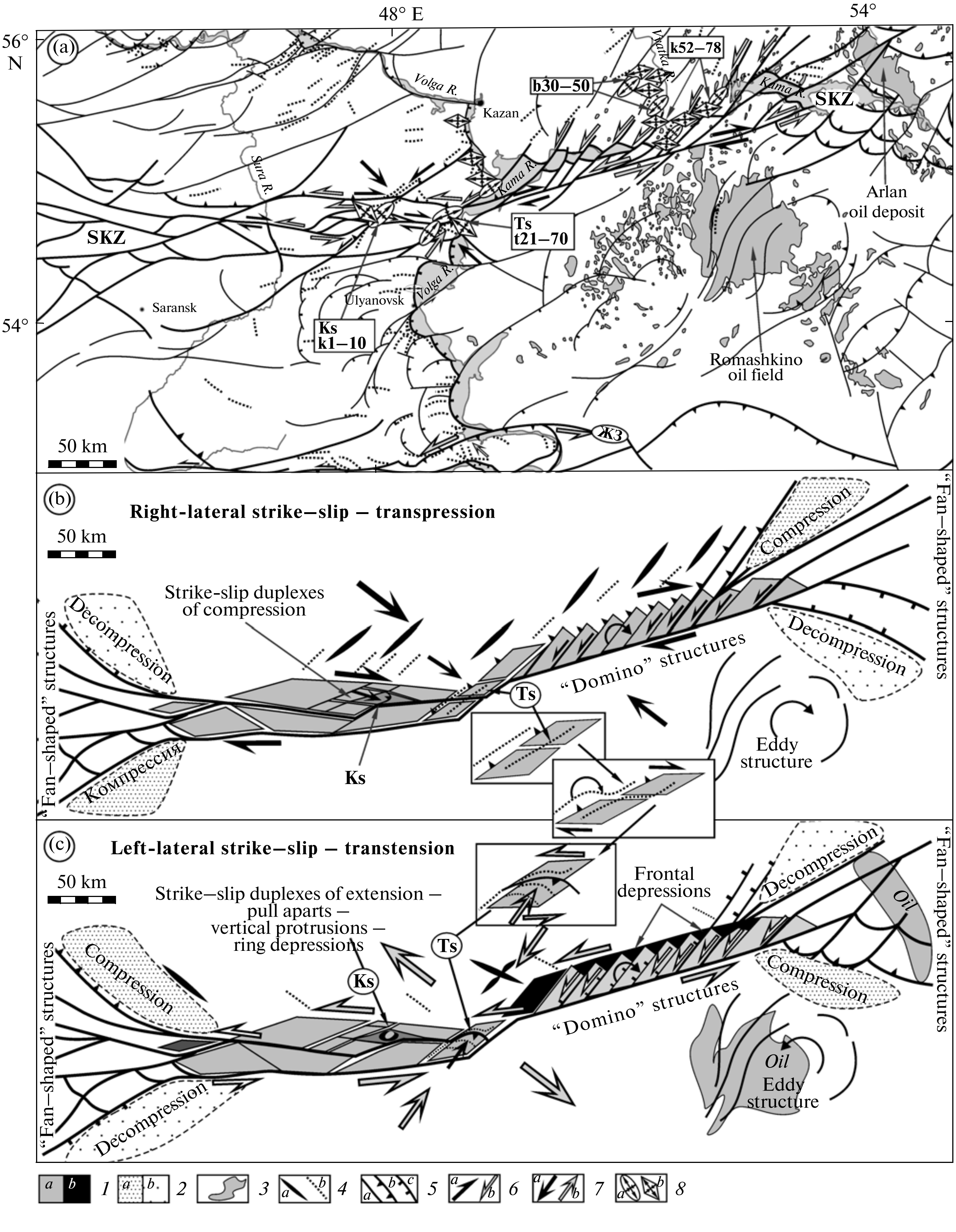
The vertical inhomogeneity of the SKZ is illustrated by seismic profiles that identify the complex combinations of fold and fracture structures of different morphology and a kinematic type (Fig. 3c–e). The fabrics of the fracture systems change in the vertical direction, and neither of them is a through fracture; they all are "blind" and "rootless." In the section there is also a disharmonic alternation of the packages with a fracture-fold and horizontal-layered (foliated?) structure (Fig. 3d, e). These phenomena are partly linked to structural–stratigraphic inconsistencies that reflect the polystage development of the SKZ. However, certain features of the general structural disharmony require other explanations. For example, strain intensity does not decrease along the SKZ section, as we would expect in the case of stratigraphic inconsistencies, but occasionally, on the contrary, increases in the upper layers. Consequently, structural disharmony mostly results from the rheological inhomogeneity and foliation of the cover, which is the main factor for the distribution of deformations. These structural phenomena are best explained by models of development of strike-slip dislocations and the features of their adaptation in a rheologically stratified medium, for example, shearing slides in the crystalline basement (or in any competent horizon) and the diagonal folds of the "plastic" cover (Fig. 8f) [42].

The lateral inhomogeneity of the SKZ is manifested in the various types of the structural organization of its several segments. The western segment of the zone is formed by a system of strike-slip duplexes, the eastern one is developed based on the "domino" structure, and the central segment is characterized by the development of the rotation-fold structures. At the zone flanks, there are isolated structures of fan-shaped virgation of faults, related to regions of the flattening of strike-slip dislocations (Fig. 11). Each of these elements is a typical form of occurrence of strike-slip zones and was repeatedly considered using the example of real natural objects and the tectonophysical models [12, 16–21, 24, 25, 27, 31, 32]. The reasons for the development of the lateral inhomogeneity can be different. In this case, one is the heterogeneous structure of the basement, including the morphology of its surface. The eastern "domino" structure of the SKZ is associated mainly with the depression, and the western system of strike-slip duplexes complicates the slope of the Tokmov arch (Fig. 1a, b). The areas of the fan-shaped virgation and flattening of the SKZ are probably related to a sharp change in the basement structure within the Kama–Belsk and the Pachelma aulacogens. The common directing role of the ancient faults in the basement in activation and reflection in the cover tectonics has been noted by many researchers [2, 5, 6, 8, 9, 13, 20]. The problem of the variations of the processes of structure formation along the SKZ strike requires additional analysis. We should mention the important role of the morphology of the buried basement surface in the development of the structural ensembles of the cover, which was likely to be connected with the features of the concentration and redistribution of the paleostresses along the inhomogeneous surface of the rheological section of the basement and the cover.

The model of tectonic evolution of the SKZ during the Alpian–Cimmerian activation illustrates the features of its tectonogenesis at the early transpressional right-lateral strike-slip stage of deformations, subsequent kinematic inversion, and the transformation of the zone to a left-lateral strike-slip transtensional structure (Fig. 11b, c). Structures having identical spatial and geometric parameters in many respects participated in the early and late stages of the deformations. The general morphology of the SKZ did not significantly change. However, the kinematic features of the high order structures changed considerably as a result of the inversion. The tectonic position of the early feathering fold–overthrust compression structures were occupied by the extension structures (normal faults, pull-apart basins). The strike-slip duplexes of the western segment of the SKZ transformed from the transpressional to the transtensional structures (see below). The tile-like "domino" structures from the eastern segment of the SKZ rotated clockwise at both stages of deformations. At an early stage, the rotation was synthetic (in accordance with the right-lateral strike slip) and was adapted by the left-lateral strike-slip component of displacements along the antithetic transpressional faults bounding the "domino tiles" (Fig. 11b). The antithetic rotation of the late stage structures (during the left-lateral strike–slip) occurred due to the left-lateral shear slide of the domains (tiles) along the transtensional faults that replaced the earlier transpressional faults (Fig. 11 c). Here, the displacements of certain "domino tiles" contributed to the formation of pull-apart frontal basins compensating the left-lateral strike slips of the domains (Fig. 11c). It is a known fact that domino structures develop indifferently in respect of the kinematics of strike-slip zones [17]. But in the case under consideration, small-scale structures of compression and subsequent extension are indicators of the general dynamic conditions and kinematic inversion of the SKZ. These features of SKZ tectonics illustrate ideas on different-rank structural parageneses, whose formation is determined in many respects by the features of reaction of the levels in the geological medium structure that are different in hierarchy from external tectonic factors [10].

As a result of rotation under conditions of early right-lateral strike–slip displacements and the subsequent layering of the later structures associated with the left-lateral strike slip, the diagonal folds of the central segment of the SKZ (the Tetyushin structure) reoriented in the space (Fig. 11b, c, insets). The rotation fold structure that was finally formed is explained most adequately by the phenomena of deep strike-slip displacements (Fig. 8e, f) and by the restructuring of

Fig. 11. Schemes illustrating the developmental features of the Sura–Kama zone of the reverse strike-slip in the Cimmerian–Alpian: a—the structural–kinematic scheme; the dynamic conditions: b—early transpressional stage (D_1), c—the late transtensional stage (D_2). The explanations are given in the text. Fig. 1 shows the designations. *1*—blocks (a) and strains (b) involved in the structure of the strike–slip zone; *2*—compression (a) and decompression (b) regions; *3*—contours of oil fields according to [37]; *4*—the axes of the swells (a) and the folds (b); *5*—mostly strike-slip faults (a), upthrows and overthrusts (b), normal faults (c); *6–8*—the symbols characterizing the dynamic conditions of the early (D_1) (a) and the late (D_2) (b) stages of deformation: *6*—orientations of the strike-slip displacements, *7*—the generalized orientations of compression (extension), *8*—the position of the principal axes of strains.


48° E
54°
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54°
(a)
Volga R.
Kazan
b30–50
k52–78
Kama R.
SKZ
Sura R.
Kama R.
Ts
t21–70
SKZ
Arlan
oil deposit
Saransk
Ulyanovsk
Volga R.
Ks
k1–10
Romashkino
oil field
ЖЗ
50 km
(b)
Right-lateral strike–slip – transpression
50 km
Compression
Strike-slip duplexes
of compression
Decompression
"Domino" structures
Ts
Decompression
"Fan-shaped" structures
"Fan-shaped" structures
Ks
Eddy
structure
Компрессия
(c)
Left-lateral strike–slip – transtension
50 km
Strike–slip duplexes of extension –
pull aparts –
vertical protrusions –
ring depressions
Frontal
depressions
Decompression
Oil
Ts
Ks
Compression
"Domino" structures
Compression
Oil
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structure
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1
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fold structures during the kinematic inversion. We should mention that in addition to normal faults against the background of the general transtention of the late stage of deformations, fold–overthrust compression structures widely occur in the central segment of the SKZ. This is caused by the fact that these structures were first partly formed during the early transpression after they underwent rotation, reorientation, and secondary crumpling at the stage of transtension. Second, conditions of deformations might have deviated locally from the general environment of the late stage transtension at this section of the SKZ. We may assume that compression structures in this case resulted from conditions preventing the development of the left-lateral strike slip in the SKZ in the segment of its bending and transition from the region of depressions (in the east of the zone) to the slope of the Tokmov arch (Fig. 1a, b, 11c).

In the regions of frontal discontinuity and flattening of strike-slip dislocations of the SKZ, the secondary feathering irregularities undergo virgation and form a fabric of a "horse tail" type. It is known that such strike-slip segments are characterized by a regular (asymmetric) location of compression and extension structures at the margins of the major zone [18, 24, 27]. The respective regions (quadrants) of increased compression and decompression are conjugated with the orientation of strike-slip displacements that they compensate. Taking data on kinematic inversion in the SKZ into account, we may assume that this phenomenon also influenced these quadrants, causing them to change places depending on the character of the strike-slip displacements (Fig. 11b, c). The analysis of this situation requires additional study, since the development of these dynamically variable compression/decompression structures in the strike-slip flanks predetermines the character of migration and redistribution of fluid–gaseous inclusions of sedimentary strata, including hydrocarbon components. One of the largest oil fields in this region (Arlan) is confined to the region of virgation and attenuation of the eastern segment of the SKZ. In this case, the anticline deposits form a kind of barrier between the segments of increased compression and decompression and is likely to mark by its position the region of migration of hydrocarbon components from the zone of compression to the segment of decompression (Fig. 11c). We may assume that, as a result of kinematic inversion, zones of different dynamic types changed places, the migration flow became reoriented, but the structural traps in the deposit area continued to catch useful components. It is expected that oil-bearing structures similar in their dynamic conditions of formation can be located within the inadequately studied western region of the frontal discontinuity and flattening of the SKZ. We also indicate the great expedience of studying the vast regions of dynamic influence exerted by the SKZ and the similar zones in the Volga–Ural region. For example, the largest Romashkino domed oil field features an eddy internal structure with respect to the location of the complicating structures, which can be associated with the pull-apart rotation in the SKZ flanks (Fig. 11c). Dynamic analogs of such structures can be discovered at the apices of the Tokmov arch (Fig. 1a).

The tectonic model of the Karlin structure (KS) characterizes the key moments of the SKZ evolution and illustrates a set of mechanisms for the formation of tectonic structures that are anomalous for the platform. The high-amplitude but local displacements of the thrust nappe, which are typical of the KS and are features of a ring structure in the presence of a depression with the central rise, were the reason for discussions. Coptogenic, karst, glaciodynamic, and tectonic models of its origin have been proposed [6, 8, 11, 33, 28, 41]. Based on structural and kinematic data considered above and taking into account the unlikely fact of a "direct" hit of a meteorite body to the strike-slip zone, the hypothesis of the impact genesis of the structure is excluded. The model proposed below inherits in many respects versions of the tectonic origin of the KS in the node of the intersection of two fractures [8, 11, 33], but complements them using the ideas of intraplate strike-slip tectonics. It is established that the KS is confined to one of the strike-slip duplexes of the western segment of the SKZ, and its development was associated with the two stages of deformations during the Cimmerian–Alpian under early transpression and subsequent events of kinematic inversion and transtension (Figs. 4, 5, 7).

The consecutive stages of the KS development are shown in the block diagrams (Fig. 12). At the early initial stage, a node was formed by the two crossing faults: the sublatitudinal (Karlin) fault, which represents one of the major zones of the SKZ, and the NE-striking Endugan fault. They are ancient deep structures that underwent activation and reached the upper segment of the section in the Mesozoic deposits from the end of Mesozoic to the beginning of Cainozoic [33]. Under transpression, they manifested as transpressional faults of moderate amplitudes, but at the node of their crossing, vertical components of displacements of each fracture were added together ($h_1 + h_2$), which resulted in the formation of a high-amplitude scarp (Fig. 12a). Later on, the left-lateral displacement along the Endugan transpressional fault led to the formation of a shear band in the plane of the sublatitudinal Karlin fault that interfered with the propagation of the right-lateral strike-slip displacements (Fig. 12b). The concentration of stresses in the area of the shear band and their subsequent relaxation caused the shear band to transform into the system of fold–overthrusts and the nappe structures of a considerable amplitude that were conjugated with the right-lateral strike-slip displacements along the Karlin fault (Fig. 12c). The latter one broke and displaced the plane of the Endugan fault, which had become relatively passive, and formed the southern flank of the Karlin strike-slip duplex. It is

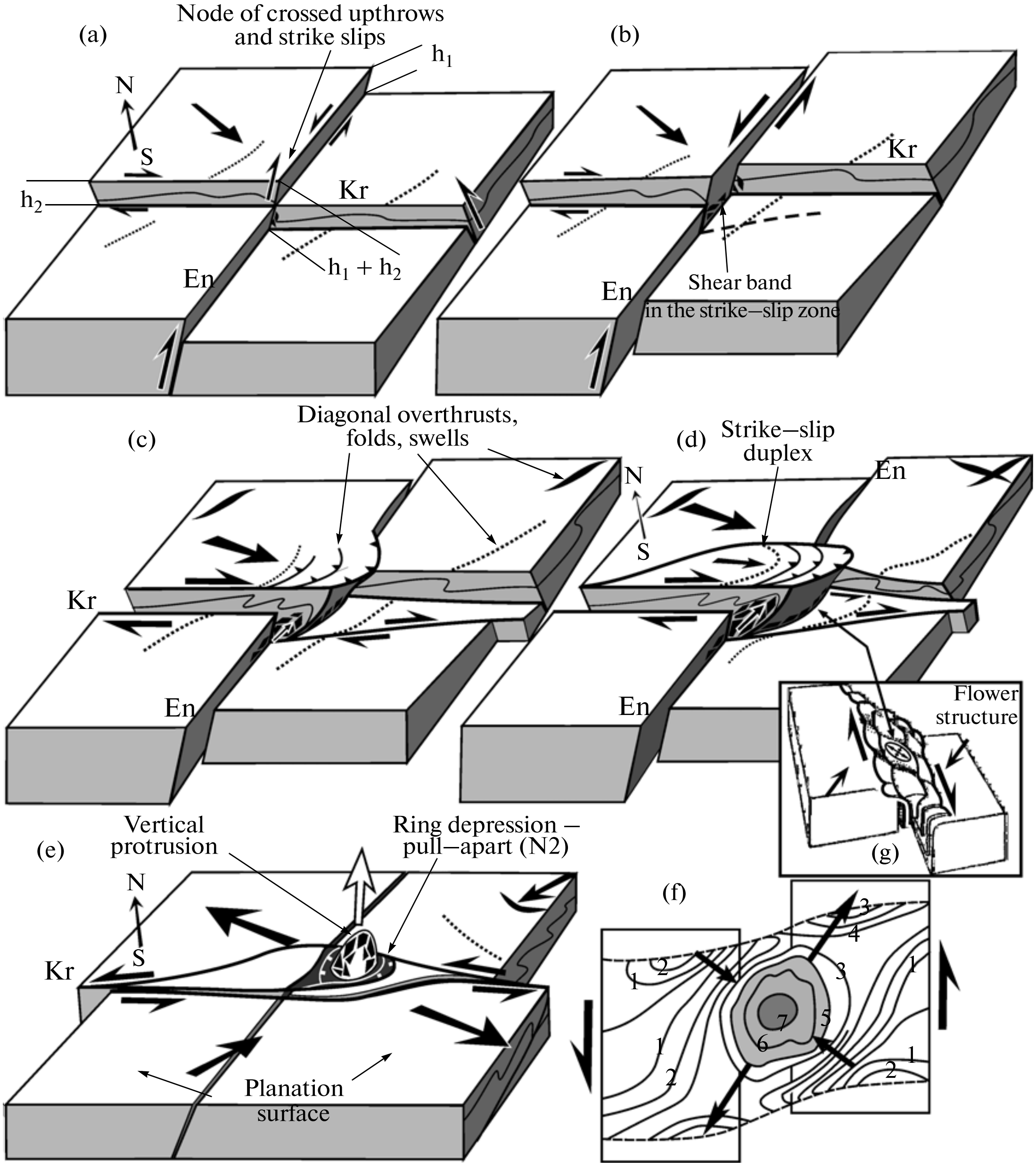

Fig. 12. Model of the Karlin structure evolution at these stages: a) initial summation of the amplitudes (h_1 + h_2) of crossed transpressional faults; b) formation of the shear band in the latitudinal strike–slip zone, c) activation of the latitudinal right-lateral strike–slip and the associated development of the fold–nappe structure; d) formation of the strike–slip compression duplex; e) kinematic inversion and development of the left-lateral strike–slip transtensional structure, vertical protrusions, and compensatory depression; f) the concentric trajectories of the maximum tangent stresses in the tectnonophysical model of strike-slip deformation according to [3]; g) the model of the lens–shaped transpressional zone (strike-slip duplexes) according to [31]. The designations are shown in Figs. 1 and 4. The explanations are given in the text.

probable that the collateral latitudinal strike-slip branch that framed the fold–overthrust structural inhomogeneity formed in the north appeared somewhat later, which finally isolated the strike-slip duplex of compression. In the central part of the latter, the transpressional fold–overthrust dislocations conjugated with compressing the substance up along the section continued their development (Fig. 12d). It is likely that the root segments of the vertical protrusions in mixtite-like brecchias began to form at this stage; however, they remained blind and reached the surface at the next stage of deformations. The lens-shape structures of the Karlin strike-slip duplex were isolated within the entire western segment of the SKZ, thus emphasizing its general similarity with the classical analogs of the transpressional zones (Fig. 12g).

The transpressional stage changed to the period of extinction of tectonic activity when the surface of

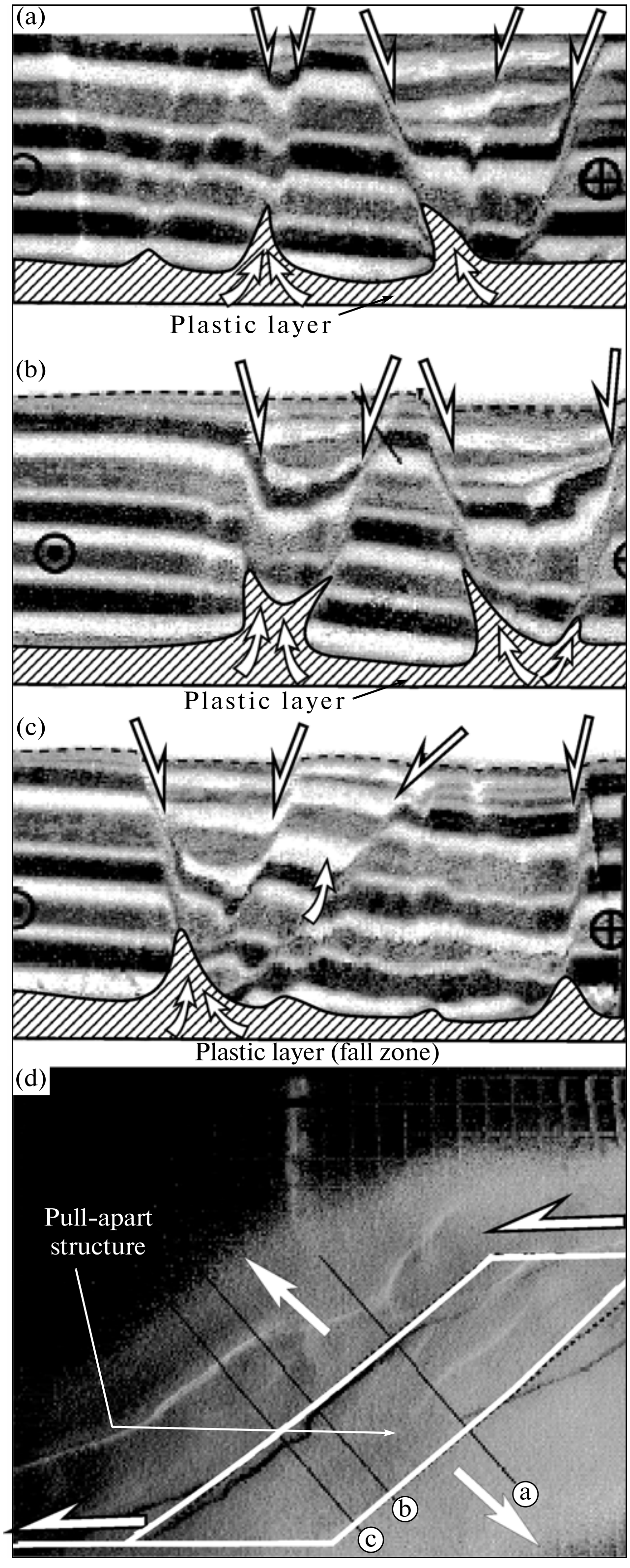

Fig. 13. Model of the formation of a pull-apart structure with a developed plastic base layer, which causes the development of injections and vertical protrusions of plastic material along the weakened zones according to [43].

washing and flattening formed. Before the beginning of the Miocene (Paleogen?) the SKZ had undergone activation and kinematic inversion related to the left-lateral strike–slip transtension. Here, the Karlin strike-slip duplex was transformed to the structure that was partly similar to a pull-apart. Fluid-saturated tectonites (mega- and mesobrecchias), which accumulated at the node of crossing of the fractures as a result of relaxation of stresses, viscous inversion, and decompression, broke through to the surface, forming the upper segment of the vertical protrusions, whose roots originated at the previous stage and were located at the depths of Middle Carboniferous deposits (Fig. 12e). The apical segments of the protrusions that were decompressed to the surface were subject to the considerable disintegration and gravity "flow," which resulted in the formation of trails of mixtite-like brecchias. The protrusions continued to develop until the early Pliocene, when the Middle Carboniferous carbonate structures were decompressed to the surface, thus forming the central rise and a compensatory ring depression on its margins (Fig. 12e). The Pliocene lake deposits, which showed the features of gravity sliding of lower layers down the slopes of the growing protruding scarp, filled up the ring depression and overlapped the central rise.

The model of KS evolution considered illustrates an example of the generation and development of the strike-slip duplex first under transpression and then under transtension. The development of these structures is a common property of many strike-slip zones, which is substantiated by numerous natural and tectonophysical models [12, 16, 17, 25, 31, 32] (Fig. 12g). The primary nodes of structural inhomogeneity (crossing of fractures and shear bands) are not obligatory for their formation. In the case under study, such phenomena explain the mechanism of the local propagation of strike-slip–overthrust displacements of anomalous amplitudes that in general are untypical of the SKZ.

An additional factor that contributed to the tectonic flow is the entry of deep fluids to the area of the KS dislocations through the highly permeable node of fracture crossing. The fluids played an important role in the processes of viscous inversion during the formation of the vertical protrusions and related mixtite-like brecchias at the second stage of deformations. This phenomenon, which is unusual under transtension at first glance, is confirmed by experimental data that indicate the possibility of the formation of ring structures in the strike-slip zone, which are associated with the concentric distribution character of the trajectories of tangent stresses (Fig. 12f) [3]. Another group of experiments on modeling the pull-apart structures, whose basement has a developed plastic layer, also illustrates the mechanism of transtentional development of injections and vertical protrusions of plastic material along the weakened zones (Fig. 13) [43]. However, we should mention that the important factors for the propogation of KS protrusions to propagate were the conditions of early transpression that favored the formation of large volumes of brecchias, the accumulation of stress in them and the development of lower structural levels of protrusions. The subsequent transtension led to the relaxation of residual loads due to the decompression of substance to the surface and the filling of the decompression cavities.

The studies by Yu. A. Morozov and his coauthors concerning the comparison of the evolution mechanisms of the pull-apart structures under transtension and subsequent transpression are especially interesting [32]. Despite the fact that the authors consider a different sequence of the structural development, many common regularities of tectonogenesis during the inversion of strike-slip displacements are recorded in the mentioned work and the above example. The regional analog of the KS is the Puchezh–Katunk structure located at 350 km towards the northwest, which is also confined to the strike-slip zone and has an identical structure in many respects [20].

CONCLUSIONS

The Sura–Kama zone (SKZ) is a deep tectonic fault that shows the features of long-term inherited and polystage development from the early stages of formation of the continental crust in the Volga–Ural craton until the Cimmerian–Alpian stage of activation.

In the Cimmerian–Alpian period of activation, the SKZ represented a zone of reciprocal (inverted) strike-slip and successive occurrence of early transpressional right-lateral strike-slip dislocations that later, during kinematic inversion under transtension, changed to left-lateral strike-slip displacements.

This zone is characterized by an inhomogeneous structure. In the longitudinal direction, it has isolated segments constructed by a system of strike-slip duplexes, according to the principle of "domino" structures and rotation fold structures. At its flanks, there are isolated segments of frontal discontinuity and fan-shaped virgation. In the vertical section of the SKZ, there are disharmonic packages where either subhorizontal foliation or fold–fracture "blind" and "rootless" structures, forming a common deep column in general, are encountered. These features are best explained by models of development of strike-slip faults in a rheologically foliated inhomogeneous medium.

The kinematic inversion and compression/decompression phenomena at the SKZ flanks, as well as the tectonic environments in the area of its dynamic influence were probably quite important during the migration and redistribution of hydrocarbon components. This aspect requires additional study for the prediction and prospecting of oil and gas deposits.

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