ISSN 0016-8521, Geotectonics, 2014, Vol. 48, No. 2, pp. 104–121. © Pleiades Publishing, Inc., 2014.
Original Russian Text © S.Yu. Kolodyazhnyi, 2014, published in Geotektonika, 2014, Vol. 48, No. 2, pp. 23–41.

Structural Assemblies of the Vladimir–Vyatka Dislocation Zone and the Position of the Puchezh–Katunki Crater, East European Platform

S. Yu. Kolodyazhnyi

Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017, Russia
e-mail: kolod@ginras.ru

Received March 11, 2013

Abstract—The Puchezh–Katunki (PK) structural unit is situated in the Middle Volga region of the central East European Platform (EEP). It is expressed as a system of complex dislocations and a meteoritic crater with a central uplift. Based on the results of structural study, the attributes of its long evolution have been revealed. Four deformation stages have been established: Hercynian (1) fold-nappe and (2) trancpressional deformations, (3) formation of the Early Jurassic impact crater and the related system of radial–concentric faults, and (4) low-amplitude tectonic reactivation of Hercynian faults during the Kimmerian–Alpine stage of evolution. In general, the PK structural unit is localized in the most strained segment of the Vladimir–Vyatka Dislocation Zone, which separates the largest structural domains of the EEP. This is a long-lived zone, which developed cyclically beginning from Paleoproterozoic collisional events and up to the Kimmerian–Alpine stage of reactivation. Such a direct impact to the cluster of concentrated deformations in one of the largest tectonic zones of the EEP seems unlikely. Nevertheless, available evidence, including the estimated stress related to the impact effect (up to 50 GPa) and its decrease with depth, does not rule out the meteoritic origin of the PK structural unit.

Keywords: within-plate dislocation zone, structural assembly, impact structure

DOI: 10.1134/S0016852114020046

INTRODUCTION

The tectonic style of platform provinces is determined in many respects by vertical movements controlling large-scale blocks and gentle folds. These tectonic manifestations are attributed to periods of relatively quiet platform evolution. Other structural elements having an Alpine-type appearance anomalous for platforms also exist against the background of this tectonic assembly. These are intraplate shear zones, strike-slip and fold–nappe dislocations, thrust faults, and tight folds and protrusions, which were repeatedly pointed out by the geologists studying sedimentary cover of the East European Platform (EEP) [1–5, 7, 11, 14, 15, 17–23, 26, 27, 30, 32, 35]. The nature and origin of these dislocations remain a matter of debate, and their origin is often explained in terms of alternative tectonic, gravitational, cosmic, and glaciodynamic concepts. The Puchezh–Katunki (PK) dislocations of the sedimentary cover and associated breccia located in the Middle Volga region of the central EEP are an example of such structural units.

Historical overview. The long-known PK dislocations are accessible to observation for tens of kilometers in the steep cliffs of the Volga River on the shores of the Gor'kovsky water reservoir (Fig. 1). They were noted by R.I. Murchison in the 19th century and remained a geological enigma for more than a century. Reviews of research and opinions on the origin of the PK structural unit can be found in [10–12]. With growing knowledge on the geology of this region, these dislocations were regarded as ancient landslides, Triassic or Quaternary glacial dislocations, a manifestation of diapirism, and injection and gravitational tectonics.

After discovery of the Vorotilovo uplift of Archean basement by drilling in the 1950s, the dislocations were explained by tectonic processes alone, in particular, by vertical displacements of the crystalline basement and landsliding of Paleozoic sequences on the slopes of the uplift [28]. Alternative hypotheses gave preference to explosion and volcanotectonic origin, e.g., to an explosion pipe [6, 30]. These views were further developed by Tumanov [33], who suggested that a multiphase explosion structure existed from the Late Permian to Middle Jurassic and that the Vorotilovo basement uplift formed in the Late Permian, subsequently emerging with the emplacement of ring and radial faults, which initiated degassing of subcrustal matter. Accumulation of gases in separate chambers gave rise to multiple near-surface explosions and crushing and shearing of rocks. The localization of this ring structure within the tectonic zone and its long-term evolution were serious arguments in favor of this

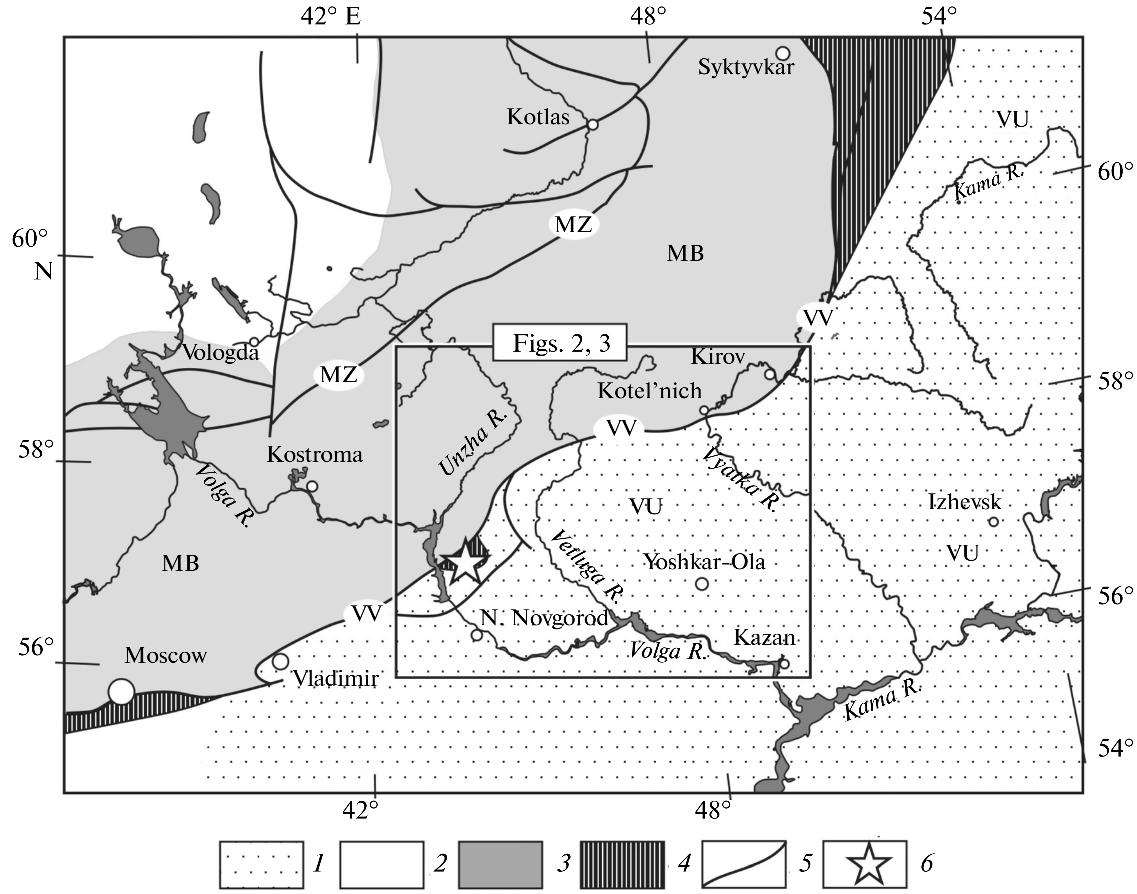


Fig. 1. Tectonic regional zones of the EEP basement, after [9]. (*1, 2*) Archean cratons: (*1*) Volgo-Uralia, (*2*) Karelian et al.; (*3*) Mid-Russian Collisional Belt; (*4*) Paleoproterozoic suture zones; (*5*) large dislocation zones; (*6*) Puchezh–Katunki structural unit. Tectonic units (abbreviations in figure): VU, Volgo-Uralia; MB, Mid-Russian Belt; MZ, Mid-Russian Zone; VV, Vladimir–Vyatka Zone.

reasoning [7, 12, 25, 28, 35]. In particular, Valeev [3–5] referred the Vorotilovo basement uplift to the Puchezh–Katunki Zone of reverse and thrust faults pertaining to the Sura–Kama system of nappes, which originated in the Precambrian and was then reactivated.

The hypothesis of the impact origin of the PK structural unit, which became an alternative to the tectonic and explosion models, is based on morphological similarity to meteoritic craters [34]. This concept was additionally substantiated by drilling of the Vorotilovo Deep Hole (5374 m) in the Vorotilovo basement uplift. Comprehensive scrutiny of cores, geological mapping (151 boreholes), and geophysical data were used to develop a 3D model of the PK structural unit. Indications of impact metamorphism and melting of rocks were revealed, and tectonic breccia within and near the crater were identified as koptogenic complexes [10].

Many researchers adopted this hypothesis. As a result, the homonymous dislocation zone vanished from tectonic and geological maps. However, in the opinion of some geologists, the absence of direct evidence for the occurrence of meteoritic matter in koptogenic complexes and localization of the PK structure within the extended tectonic zone leaves open the question of its origin [12, 35].

Research methods. Without a goal to corroborate or deny either hypothesis, a structural study of the large tectonic zone, to which the PK unit is related, was carried out. The structural–kinematic methods and paragenetic analysis considered in [16, 17, 21, 24] were used during the fieldwork. The FaultKin6 software [37] was applied to process structural data, e.g., to analyze the orientation and sense of striation. A remote study of structural elements based on interpreting digital topography maps, aerial photographs, and satellite images was also used. From a multitude of revealed lineaments, systems linked to sedimentary cover and basement structures expressed as contour lines, as well as to configurations of gravity and magnetic anomalies, were chosen. The preliminary kinematic identification of faults was carried out on the basis of a study of structural patterns [21, 24]. The remote sensing results were refined during fieldworks.

TECTONIC SETTING OF THE PK STRUCTURAL UNIT

The geological and geophysical data shows that the PK structural unit is related to the extended tectonic zone, which is expressed at all structural stages of the platform and supported by the configuration of magnetic and gravity anomalies. According to [9], this zone is an important tectonic boundary in the crystalline basement of the EEP as the suture zone that bounds the Mid-Russian segment of the giant Paleoproterozoic Lapland–Mid-Russia–South Baltia collisional orogen in the southeast (Fig. 1). This zone is marked by exposed Paleoproterozoic volcanic–sedimentary belts, which are most completely represented in the southwest and northeast of the area under consideration. Approximately from the town of Vladimir to the upper reaches of the Vyatka River, these belts pinch out and the fault zone, plunging to the northwest, serves as the immediate boundary between the Mid-Russian Belt and the Neoarchean Volgo-Uralia province of the EEP [9]. Further, this boundary will be called the Vladimir–Vyatka (VV) dislocation zone (Fig. 1).

At the level of the crystalline basement, the VV zone is distinguished by significant complication of its surface morphology as compared with the adjacent regions (Fig. 2). Contour lines on the map of the basement surface topography show that this disturbance is a system of high-order faults, which make up a belt 30–60 km in width. The Vorotilovo basement uplift with a vertical amplitude of ~2 km is localized in the southwestern part of the VV zone, which widens toward the northeast and then crosses and disturbs the Kotel'nich Arch. Afterward, gradually narrowing, the zone merges with the normal fault system bordering the Riphean Vyatka–Kazhim Aulacogen (Fig. 2). Along most of its extent, the VV zone separates the Moscow Syneclise and the Volga–Ural Anteclise, where the slope between these structural units becomes steeper. The tectonic position of this zone is also consistent with the regional structure of sedimentary cover, in particular, with configuration of contour lines of the Vereya Horizon of Middle Carboniferous (Fig. 3a).

The configuration of the VV zone at the level of present-day erosion surface imitates the structural pattern of the basement surface in many respects (Fig. 3a). The zone is clearly expressed in the topography, in particular, at intersections with large streams, where sharp arcuate and knee-shaped bends of valleys are observable (Fig. 3b). A system of lineaments characterized by regular combination of the master (longitudinal) and splaying (diagonal) strike-slip faults of R and R' types has been identified in the central and northeaster segments of the VV zone. The tectonic swells oriented along the strike of this zone and diagonally to the strike have also been revealed here [12, 13]. In general, this is evidence for the development of strike-slip dislocations (Fig. 3). The northeastern segment of the VV zone merges smoothly with system of Vyatka–Kazan dislocations, also known as a homonymous system of inverted swell-like structural elements of the cover located above the Riphean Vyatka–Kazhim Aulacogen [13, 22] (Fig. 3a). In the southwestern sector of the zone, where the PK structural unit and a general sigmoid bend are noted, arcuate scalloped systems of faults and crosscutting lineaments make up a structural pattern characteristic of strike-slip–thrust zones (Fig. 3b).

The results of such interpretation have been verified by field observations along the Volga, Unzha, Vetluga, and Vyatka river valleys. Variably deformed Upper Permian, Lower Triassic, Jurassic, and Lower Cretaceous sedimentary rocks participate in the structure of the VV zone. The most significant folds and faults have been identified in Permian sedimentary rocks. In Mesozoic rocks, the intensity of folding and faulting markedly decreases: gentle folds and homoclines with dip angles lower than 20° predominate; however, fracture zones, brecciation, and sporadic tectonic melange are also widespread. The intensity of deformation in Permian beds reaches a maximum in the southwestern sigmoid sector of the VV zone. It is as though the PK ring depression, which is situated exactly here, is stitched through the Vendian–Paleozoic and Lower Triassic sedimentary rocks, is filled with the Lower Jurassic breccia, Middle–Upper Jurassic and Lower Cretaceous sedimentary rocks largely buried beneath Neogene and Quaternary sediments.

GEOLOGY OF THE PK STRUCTURAL UNIT

Let us consider the geology of the PK structural unit (depression) using recent and older publications [3–5, 7, 8, 10–12, 14, 15]. This structural unit is distinguished by a high degree of roughness of the crystalline basement surface (Fig. 4a). The systems of linear and arcuate uplifts within this depression envelop the stocklike Vorotilovo basement uplift. Having a vertical amplitude of ~2 km, this uplift pierces through the sedimentary cover at the center of the PK depression, almost reaching the erosion surface. Scarps hundreds of meters in amplitude are outlined along its slopes. The basement rocks are enveloped by thick (hundreds of meters) aprons of megablock breccia grading into allogenic breccia of crystalline rocks [10]. Because a distinctly expressed basement roof is not observed, interpretations of the uplift morphology are rather diverse [7, 10, 12].

Vendian claystones, Middle and Upper Devonian terrigenous–carbonate sequences, Carboniferous carbonate rocks, Lower Permian anhydrite–carbonate rocks, and variegated terrigenous beds of Upper Permian and Lower Triassic have been drilled in the framework of the PK depression. The total thickness of the cover varies here from 1.8 to 2.5 km (Fig. 4a).

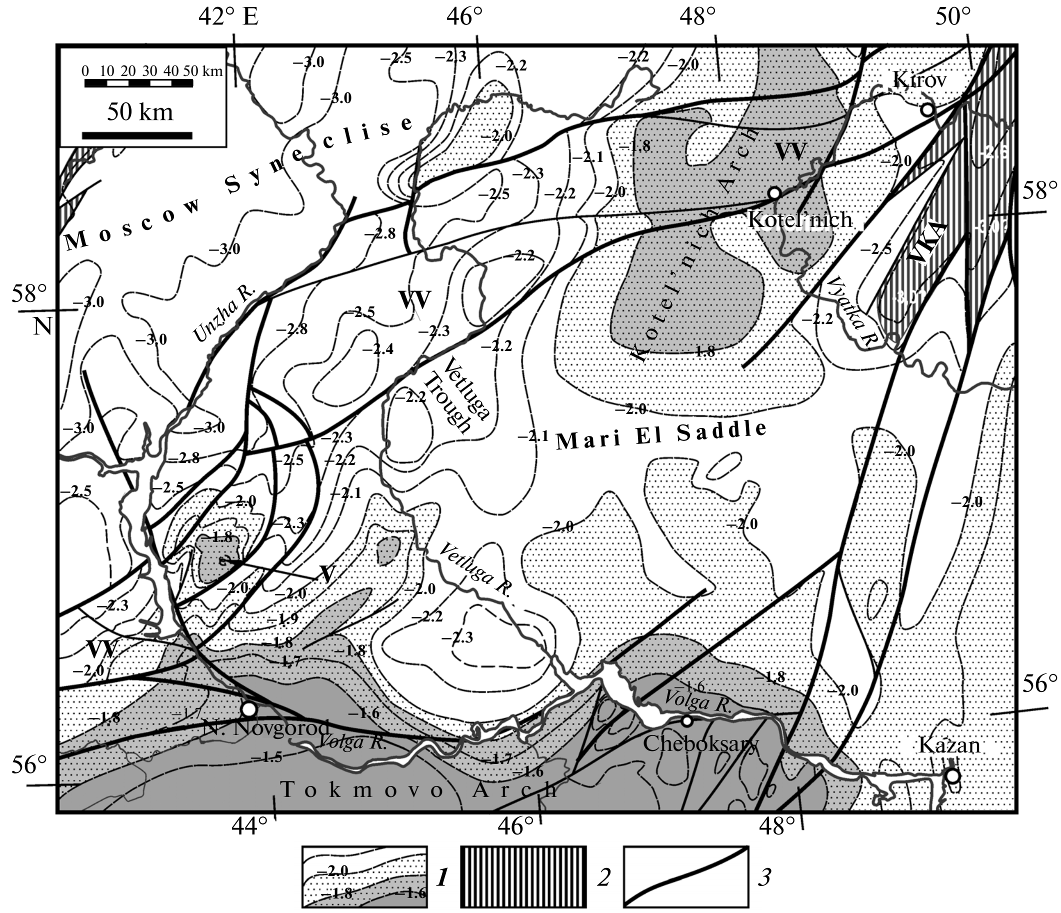


Fig. 2. Structural map of crystalline basement surface of the Volga–Vyatka region, after [7, 8, 10, 12, 13]. See Fig. 1 for the map location. (*1*) Contour lines of crystalline basement roof (contour lines of basement elevation are given in km); (*2*) Riphean aulacogens; (*3*) faults. Structural units (abbreviations in figure): VKA, Vyatka–Kazhim Aulacogen; VV, Vladimir–Vyatka Zone; V, Vorotilovo basement uplift.

The PK depression, nearly isometric in plan view and ~70 km in diameter, is outlined in the sedimentary cover by structural and lithological features (Figs. 4b, 4c). Socle, koptogenic, filling, and overlying complexes are distinguished. The deformed Archean crystalline rocks and overlying cover, Vendian to Lower Triassic in age, make up the socle; a crater formed in its body. The central uplift (Vorotilovo basement uplift) and surrounding ring trench 40–42 km in diameter, which is traced to 1900 m in depth, are the main morphological elements [10]. The deepest part of the trench cuts down the Vendian rocks. A system of stepwise scarps and a building-up ring terrace at the crater margin develop along the outer perimeter of the ring depression (Fig. 4c). The ring funnel is partly filled with the Lower Jurassic koptogenic complex of breccias and impactites, which formed during crater formation in the socle. Middle–Upper Jurasic, Lower Cretaceous, and Cenozoic sedimentary rocks make up the filling and overlying complexes [10].

The outer boundary of the ring terrace is determined by the contour of the Lower Jurassic allogenic breccia (Figs. 4b, 4c). In the northern PK structural unit, the socle is largely composed of Lower Triassic rocks, whereas in the southwestern and southern parts, Upper Permian sedimentary rocks predominate. The seismic profiling shows that a number of ring swells and related reverse faults waning away from the epicenter are outlined in the Paleozoic socle of the terrace and trench (Fig. 4c). In addition to concentric faults, the ring terrace is complicated by a system of radial trenches with sharply increasing thickness of koptogenic breccia. Their depth reaches 180 m at a width of 1–6 km and tens of kilometers in extent.

The ring trench is primarily filled with koptogenic megablock breccia consisting of klippen and blocks of Paleozoic and Vendian rocks hundreds of meters in size (Fig. 4c) and 0.8–1.5 km in thickness. The boundary between megablock breccia and intact socle rocks is conventional [10]. As follows from the drilling results, a complex juxtaposition and thrusting of sheets and blocks of rocks complexes different in age have been established; recurrent sections and their overturned successions are noted. In earlier publications,

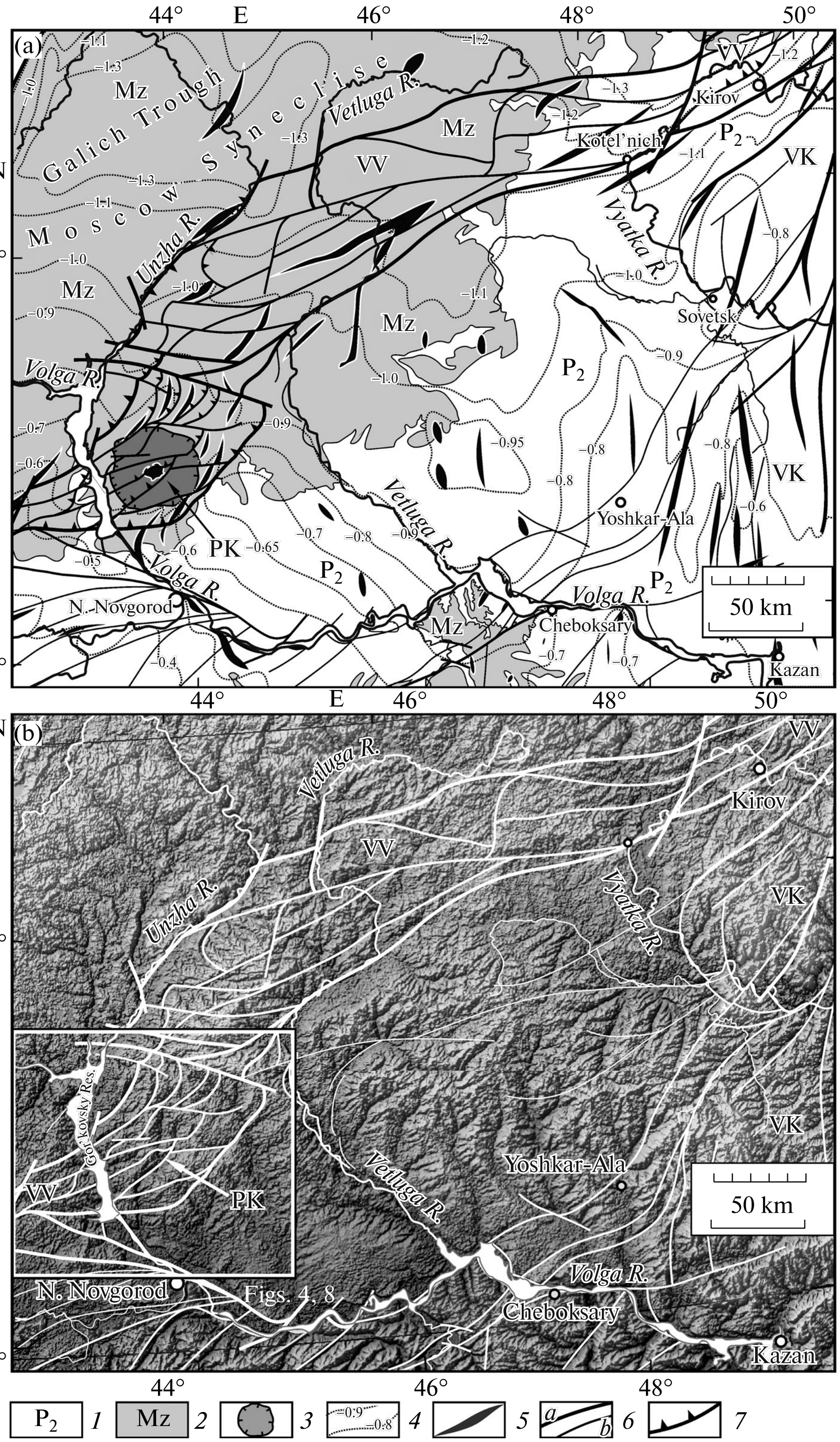


Fig. 3. Schematic structural maps of Volga–Vyatka region: (a) tectonic structure of Phanerozoic cover, after [12, 13, 31] and (b) interpretation of digital topography map. See Fig. 1 for location. Panel (a): (*1*) Upper Permian and (*2*) Mesozoic rocks; (*3*) Puchezh–Katunki Depression; (*4*) contour lines (in km) of roof of the Vereya Horizon, Moscovian Stage, Middle Carboniferous; (*5*) swell-like structural elements; (*6*) lineaments, strike-slip and reverse–strike-slip faults: (a) master and (b) auxiliary; (*7*) reverse and thrust faults. Structural units (abbreviations in figure): VV, Vladimir–Vyatka Zone; VK, Vyatka–Kazan Zone; PK, Puchezh–Katunki structure. Panel (b): white lines are faults.

these rocks were regarded as a wide zone of fold–thrust dislocations surrounding the Vorotilovo uplift [3–5, 7, 11, 28]. Recently, they have been described as a koptogenic complex [10]. On the one hand, this interpretation solved the problem of folding, and on the other, the built-up thickness of koptogenic rocks and a depth of the PK crater almost by five times.

Megablocks and klippen are overlain by rubble and block polymictic breccia, as well as locally developing suevite and koptoclastites up to 400 m thick. Variegated rubble–block breccias consisting mainly of fragments of Permian and Triassic rocks are widespread at the margins of the depression and at the ring terrace. In the ring depression, these typically koptogenic rocks are overlain by Middle Jurassic sediments of the crater lake up to 340 m thick, which are, in turn, overlapped by Upper Jurassic, Lower Cretaceous, and Cenozoic beds up to 162 m in total thickness [10].

Numerous signs of impact and thermal metamorphism have been established in crystalline rocks of the Vorotilovo uplift. According to the results of drilling the Vorotilovo Hole (5374 m), the Archean crystalline rocks are severely fragmented, cut by tagamite veins, pseudotachylites, and cataclasites [10]. Shock transformations are expressed as shatter cones, fracturing, and brecciation; diaplectic alteration of minerals; their transition to disordered and high-density phases (diamonds); and melting. The estimated stress related to the impact event reaches a maximum (45–50 GPa) in the upper part of the Vorotilovo Hole and gradually decreases toward its bottom (15–20 GPa) [10]. The K–Ar age of impact glass and tagamite covers a time interval from 200 ± 3 to 183 ± 5 Ma [10]. The age of sediments overlying koptogenic breccia corresponds to the Middle Jurassic.

STRUCTURE OF THE WESTERN WALL OF THE PK STRUCTURAL UNIT

The structural assemblies of western wall of the PK structural unit have been studied in sections exposed along the cliffs of the Volga River and the banks of the Gor'kovsky water reservoir. Variegated sedimentary rocks of the Upper Permian (Tatarian Stage) and Lower Triassic crop out here as the socle complex of the ring terrace, which is overlapped with structural and stratigraphic unconformity by the Lower Jurassic koptogenic rubble–block breccia (Fig. 4b). The entire rock complex is complicated by folds and faults, the character and intensity of which vary in the lateral direction and from one rock complex to another.

The most intense deformations are observed in the Permian sedimentary rocks in the southern part of the Gor'kovsky water reservoir within a belt up to 30 km wide. The rocks are disturbed here by frequent fault zones oriented in the near-latitudinal and east-northeastern directions and reaching hundreds of meters in width. The beds are intensely folded within these zones. Deformations gradually wane toward the walls. In general, the zones of intense and weak deformation are linked by gradual transitions and alternate throughout the section. Triassic rocks and Jurassic koptogenic breccia are distinguished by another style of dislocations and a much lower degree of deformations (see below).

The Permian rocks underwent multiple deformations. The intercalating claystone, limestone, and sandstone beds are deformed in various folds disturbed by a complex system of faults pertaining to different generations (Fig. 5). Mutual intersections and superposition studied during fieldwork are denoted as D_1–D_4 in sections (Fig. 5). Such sections are the basis for systematization and classification of measurements characterizing the orientation of structural elements.

Statistical analysis of bedding orientation in Permian sedimentary rocks. The poles make up two major and one auxiliary dispersion girdles (Fig. 5c, diagram I). The first is the arc of the great-circle girdle and characterizes cylindrical folds (F_1), the axial planes of which are ENE-trending and incline north-northwest. The second is the arc of the small-circle girdle and characterizes conic folds with near-latitudinal orientation of the axial planes (F_2). The third is poorly expressed along the arc of the great-circle girdle and is probably related to the third generation of folds. The first two fold systems are almost coaxial: the angle between their axial planes is 20°. Measurements of the hinge orientation of small folds are primarily consistent with the geometrically found hinges of large folds.

Statistical analysis of striae orientation on slickenside surfaces shows that bulk processing of these data is incorrect. We undertook a classification of these data based on structural observations. As a result, four kinematic groups of dislocations have been revealed. The first group (generation) comprises thrust faults gently dipping north-northwest; their hanging walls are overthrust south-southeast (Fig. 5c, diagram II). The second group combines a complex structural assembly of divergent reverse, reverse–strike-slip, thrust, and strike-slip faults corresponding to a setting of near-meridional compression (transpression) (Fig. 5c, diagram III). The directions of horizontal compression for these two groups of dislocations estimated using FaultKin6 are consistent with the orientation of folds (Fig. 5c, diagrams I–III). The third kinematic group of dislocations reflects the complete inversion of the principal deformation axes and corresponds to normal faults characterizing the NNW–SSE-trending horizontal extension (Fig. 5c, diagram IV). The fourth group of dislocations is almost completely identical to the structural elements of the second and, partly, the first generations in respect to the kinematics; they are expressed in the Permian beds as reactivation of faults in the form of low-amplitude offsets.

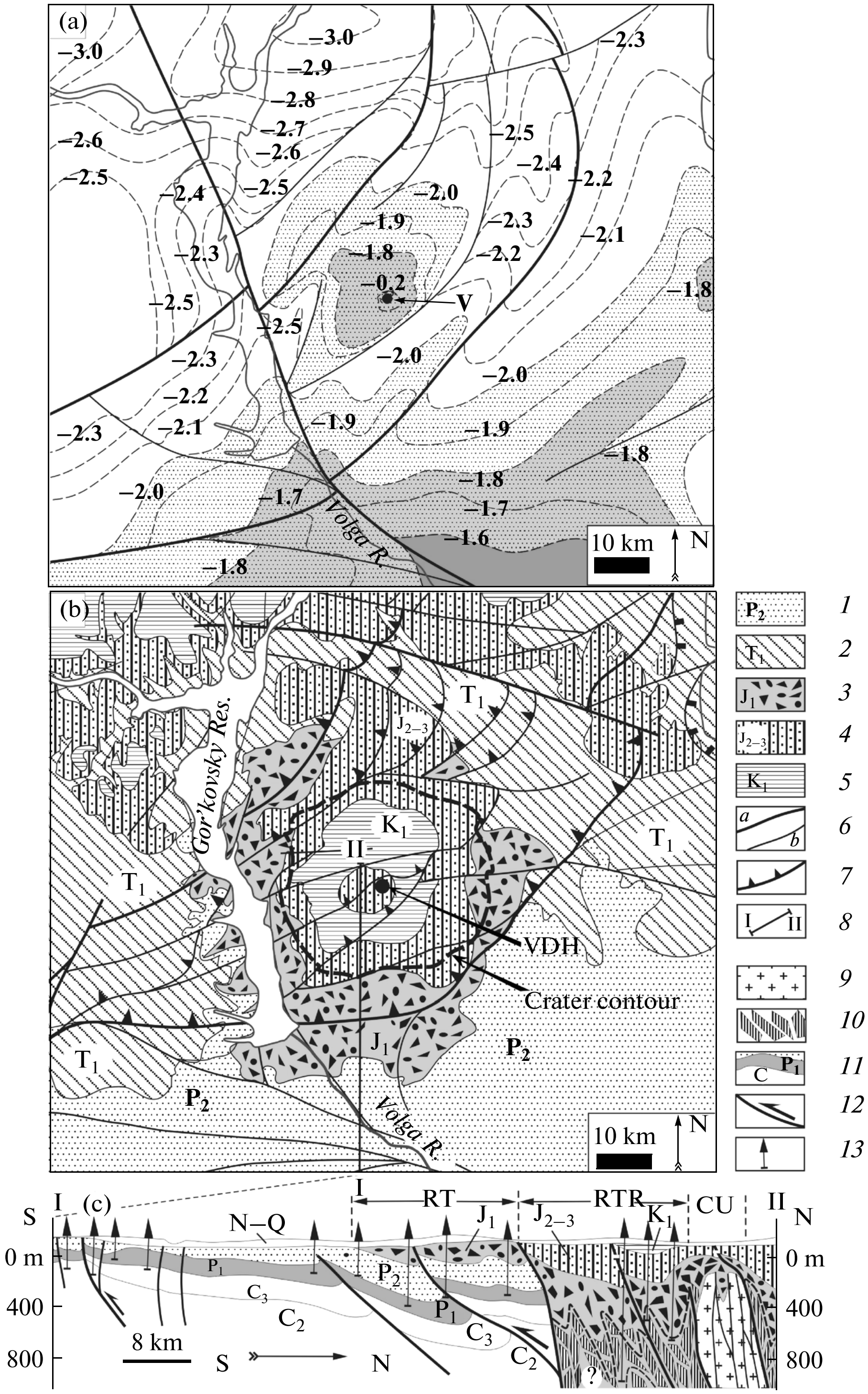


Fig. 4. Puchezh–Katunki structural unit, after [3–5, 7, 10–12]: (a) structural map of basement roof (see Fig. 2 for legend), (b) geological–structural map, (c) geological–structural section along line I–II. See Fig. 3b for the map location. Panel (b): (*1–5*) rock sequences: (*1*) Upper Permian, (*2*) Lower Triassic, (*3*) Lower Jurassic (koptogenic breccia), (*4*) Middle and Upper Jurassic, (*5*) Lower Cretaceous; (*6*) strike-slip and reverse–strike-slip faults: (a) master and (b) auxiliary; (*7*) reverse and thrust faults; (*8*) section line; additionally in panel (c): (*9*) Archean gneiss; (*10*) megablock breccia (fold–thrust structure ?); (*11*) Carboniferous and Lower Permian rocks; (*12*) fault and offset direction; (*13*) borehole. Abbreviations in figure: V, Vorotilovo basement uplift; VDH, Vorotilovo Deep Hole; RT, ring terrace; RTR, ring trench; CU, central uplift.

STRUCTURAL ASSEMBLIES AND THEIR RELATIONSHIPS

Four generations of structural assemblies have been recognized in the PK depression.

Structural assemblies of the first generation (D_1) are represented by folds associated with nappes and tectonic melange zones retained as relics against the background of superposed deformations. Early overturned, recumbent, and plunging folds are associated with thrust faults and melange zones, which partly or completely cut off their limbs (Fig. 5a, center and north; Fig. 5b, north). A complex fault system complicates the cores of these structural elements (Fig. 5a, north). The impression is given that the bedded sequences is transformed into a megabreccia and lost its integrity. Nevertheless, the key beds make it possible to restore its structure, disturbed by a regular fault system (Fig. 6a). The horizontal displacements of folds passing into nappes are measured at tens of meters. Torn-off hinges are noted in their frontal portions (Fig. 6b). Mesostructures of this generation (foliation, cleavage, asymmetric folds) are identified from the superposition of younger structural elements (Figs. 6b–6d). Zones of tectonic melange, which surround folds passing into nappes, are traced for many tens of meters (Fig. 5a). Their apparent thickness reaches 7–8 m. They are composed of lenticular foliated and mixed clay matrix incorporating lenses and chains of marmorized limestone boudins; folds of ductile flow; and flaser structures (Figs. 6d; 5a, south). In general, the zones of tectonic melange are gently dipping and complicated by superposed folding and faulting, which markedly distorted their primary kinematic attributes. Judging by localization of recumbent anticline hinges, thrusting was oriented toward south-southeast.

Structural assemblies of the second generation (D_2) predetermine the main style of dislocations in Permian sequences. They are represented by reverse, reverse–strike-slip, and thrust faults, as well as by folds diverse in morphology (Fig. 5). Asymmetric tight, occasionally overturned conic folds are predominant (Figs. 7a; 5a, 5b, center). The associated reverse and strike-slip faults cut off their limbs and disturb their cores. The cleavage, fanlike with respect to axial planes of folds, is widespread. Disharmonic injection folds and a multifold increase in the thickness of plastic layers formed as a result of ductile flow and squeezing-out of matter from limbs into the hinges of folds (Figs. 7a, 6c). Relics of earlier deformations are noted in the hinge segments of folds as hinge-in-hinge structures and intersections of differently oriented systems of foliation and cleavage (Figs. 7a, 6c).

This system of folds and reverse–thrust faults make up divergent palm structures, where folded tectonic packets are arranged symmetrically relative to steeply dipping reverse–strike-slip zones of intense foliation up to 10 m wide (Fig. 5b, center). The splaying reverse faults, diverging apart from the stem zone often flatten and are transformed into thrusts and systems of thrust duplexes (Fig. 7b). Similar in many respects divergent structures are noted in limbs of synformal folds, which have been detached and thrust into opposite directions (Fig. 5b, south). The dynamic simulation allows us to suggest that such a divergent structure occurs within zone of squeezing and descending sucking. The secondary convergent zones (stitching structures) arise between adjacent divergent structural elements (Fig. 5b, south and center). In general, the given assembly combining divergent palm structures with upward squeezing or downward sucking of rocks is typically transpressional.

The structural elements of the first and second generations are characterized by almost coaxial position of horizontal compression axes mainly oriented in the NNW–SSE direction (Fig. 8a, diagrams). Structural assemblies of these stages were observed only in the Upper Permian sedimentary rocks and not detected in the overlying Mesozoic rocks. The faults of D_{1-2} system underwent reactivation and penetrated into Mesozoic rocks as a result of the latest deformation (D_4) (Figs. 8a, 4b, 4c). However, at the upper levels they are quite different low-amplitude structural elements without completely developed folding. Such renewed faults reach present-day surface and are expressed in the topography as late dislocations (D_4).

Structural assemblies of the third generation (D_3) are represented by a system of normal and normal–pull-apart dislocations, whose surfaces are broadly conformable to preceding thrust and reverse faults. The normal faults crosscut and displace thrust and reverse faults of older generations and zones of tectonic melange. Their conjugate development occasionally resulted to the formation of stepwise half-graben systems (Figs. 5a, south; 6d).

In contrast to the older structural elements of horizontal compression localized along fault zones, the extension structures are distributed relatively uniformly throughout the studied Permian–Triassic section and also occur at the sites devoid of older folds. In the latter case, it is clearly seen that normal faults are listric with antithetic rotation of blocks (Fig. 9a). They gradually flatten with depth merging with bedding planes. Mesostructures with normal kinematics are widespread. These are numerous fractures with slickensides and conjugate X-shaped minute normal faults indicating horizontal orientation of extension axis (Fig. 9b). When a pull-apart component increases, clasitc dikes up to 0.5 m thick are formed along normal faults (Fig. 9d).

The vertical separation along normal faults reaches many tens of meters. The high-amplitude normal fault shown in Fig. 9c is noteworthy. This fault cuts off slightly deformed sedimentary rocks of the Tatarian Stage and forms the southern wall of a large graben filled with Lower Jurassic koptogenic breccia (Fig. 9c). The master normal fault is accompanied by secondary

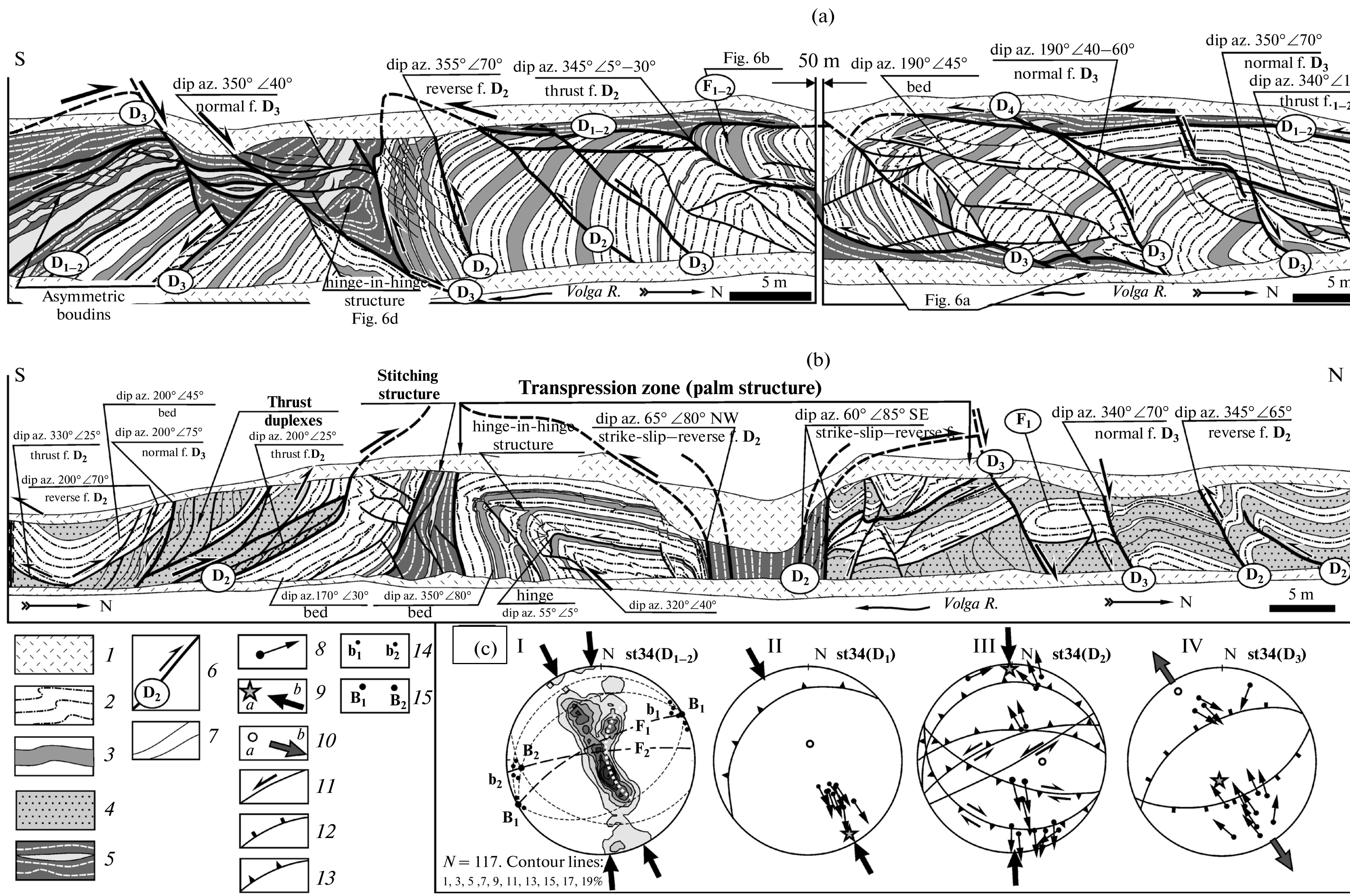


Fig. 5. (a, b) Geological–structural sections of deformed sedimentary rocks of Tatarian Stage, Upper Permian (stake 34 in Fig. 8); (c) stereographic projections on lower hemisphere: (I) bedding poles, (II–IV) fracture and fault poles with displacement vector of hanging wall for deformation stages D_1, D_2, and D_3, respectively. Panels (a, b): (*1*) Quaternary sediments; (*2–4*) beds of Tatarian Stage: (*2*) claystone and marlstone, (*3*) limestone, (*4*) sandstone; (*5*) zones of tectonic boudinage and melange; (*6*) fault, slip direction, and deformation stage (D_1–D_4); (*7*) shear fracture. Panel (c): (*8*) fault plane and displacement vector of hanging wall; (*9, 10*) principal deformation axes (*a*) and their projection on horizontal plane: (*9*) compression and (*10*) extension; (*11–13*) averages position of fault planes of (*11*) strike-slip fault, (*12*) normal fault, (*13*) reverse and thrust faults; (*14, 15*) hinges of folds of the first and second generations: (*14*) measurements at outcrops (b_1, b_2) and (*15*) found from geometry (B_1, B_2); F_1 and F_2 are axial planes of folds (first and second generations).

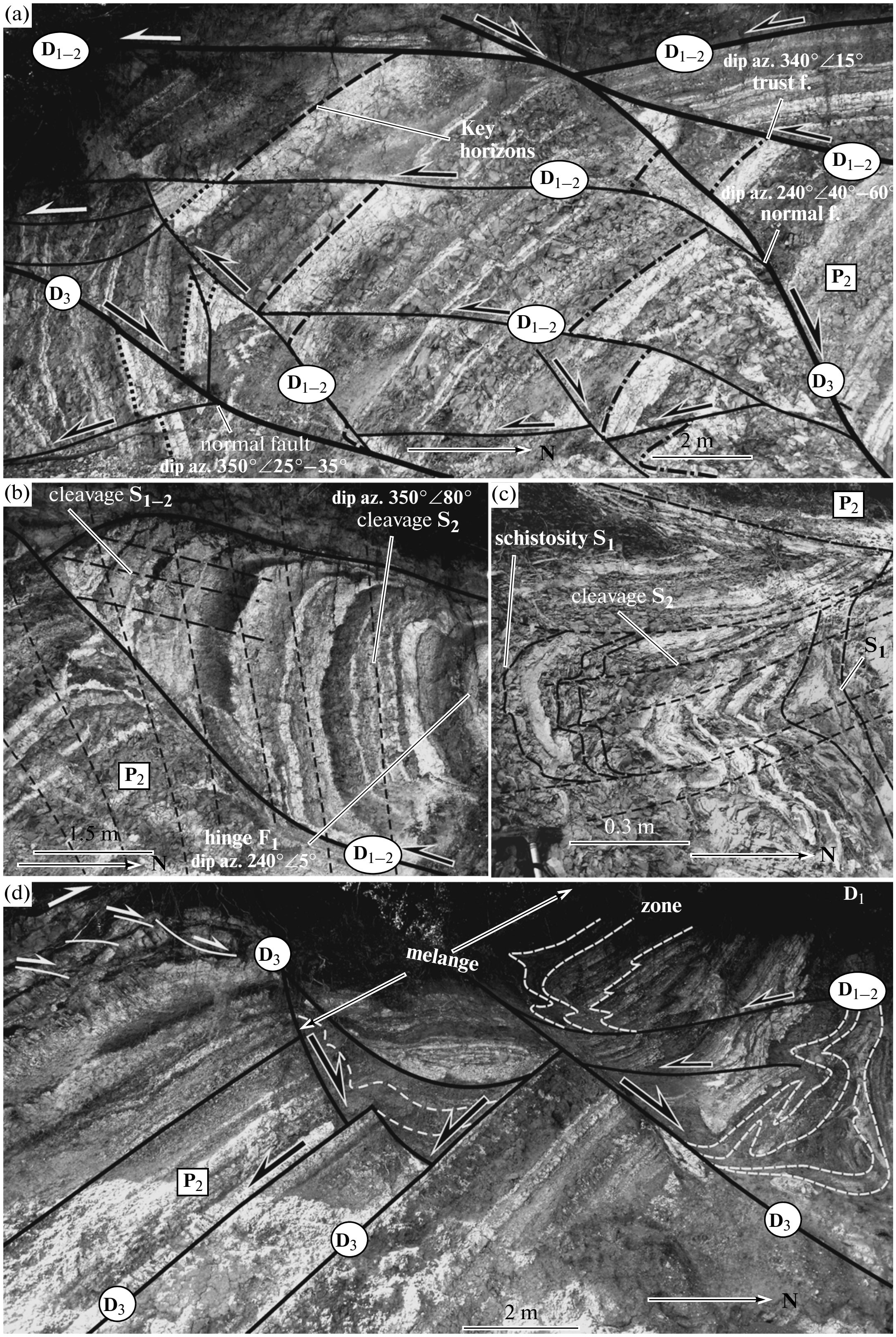


Fig. 6. Deformed Upper Permian rocks (photographs from southern part of the Gor'kovsky reservoir): (a) structural relationships between various fault generations in core of recumbent fold F_1; (b) torn-off hinge of recumbent fold F_1; (c) disharmonic folds of ductile flow and intersections of planar mesostructures related to different generations; (d) tectonic melange zone (D_1) and system of crosscutting normal faults (D_3). See Fig. 5 for explanation of symbols.

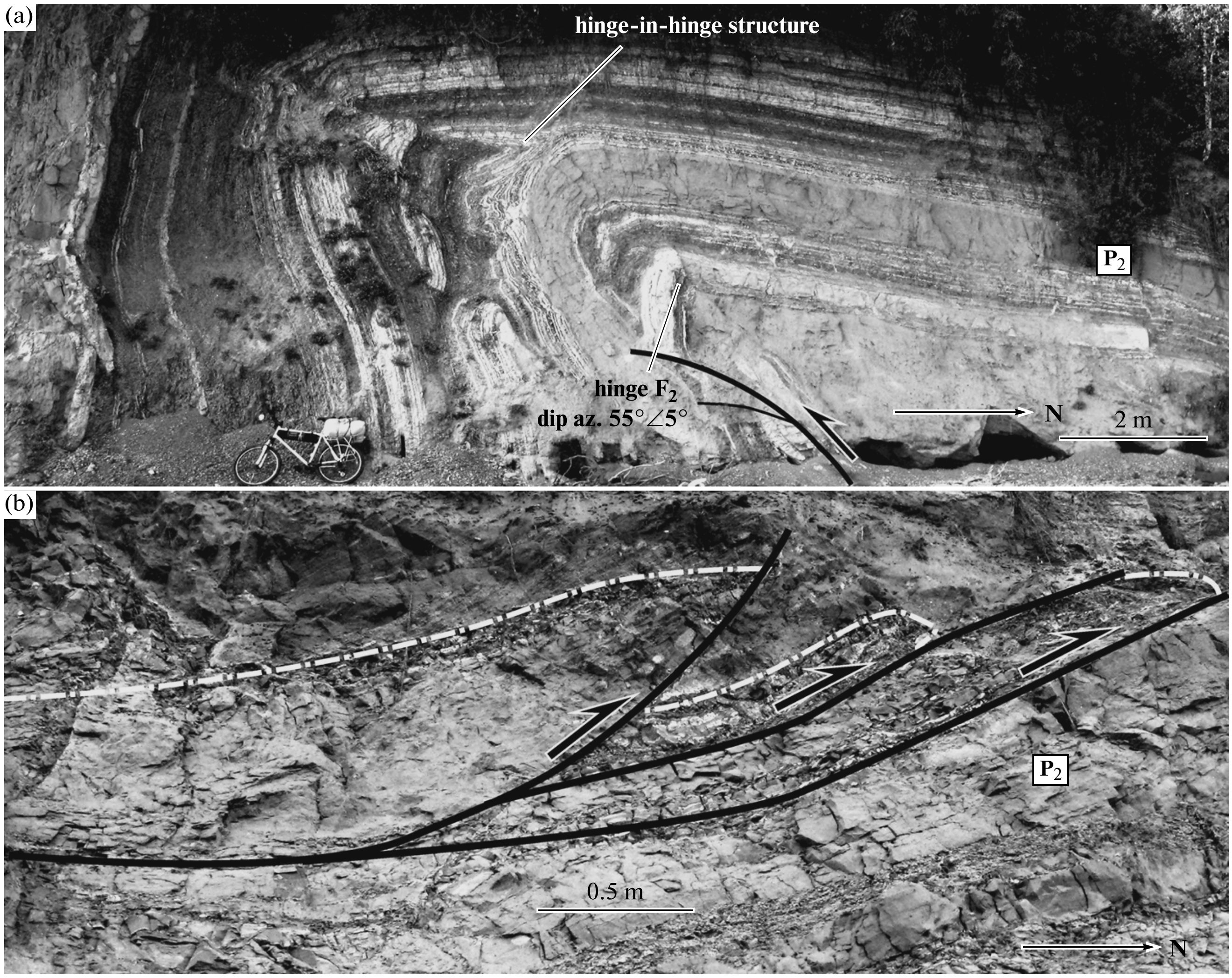


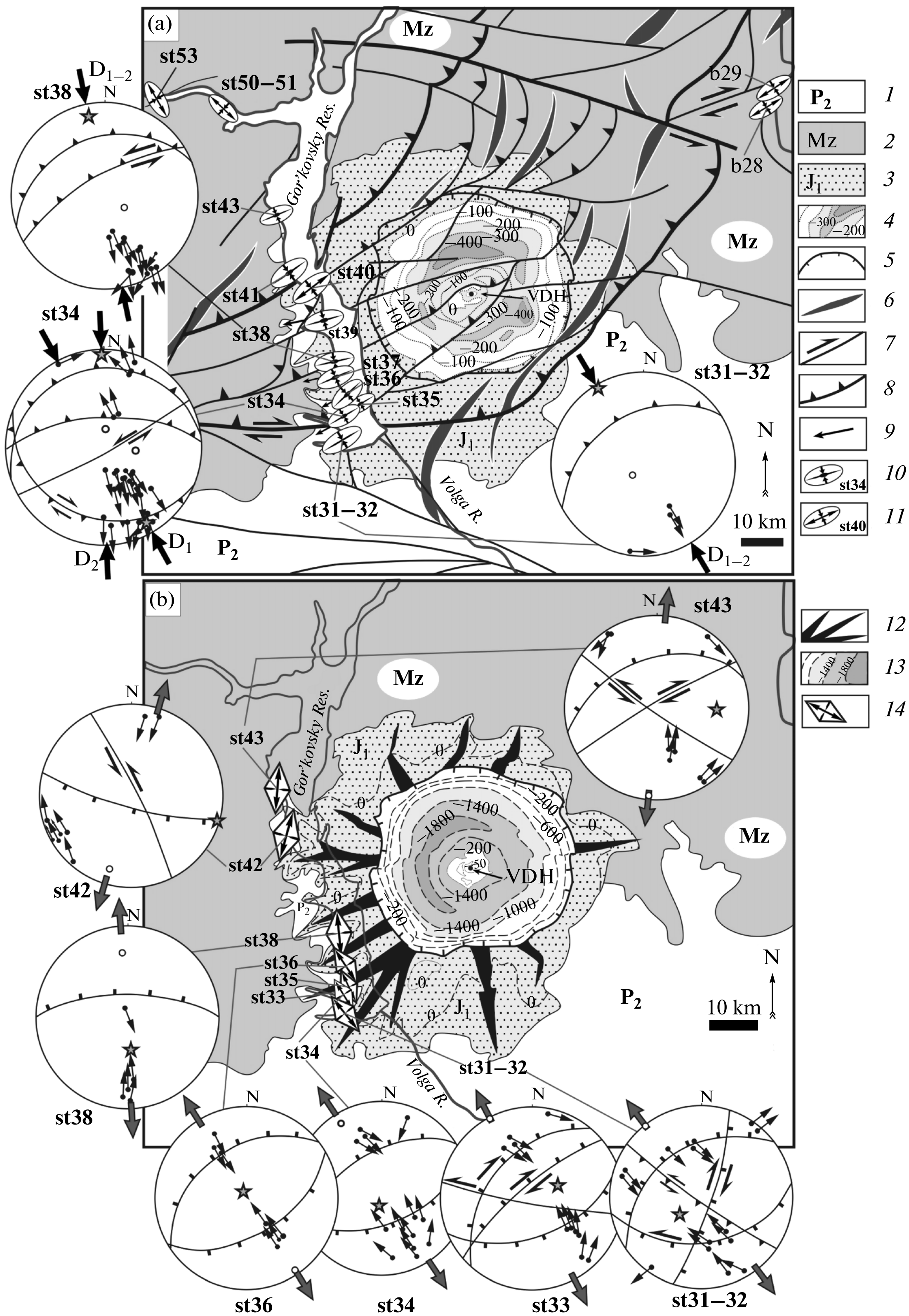
Fig. 7. Structures of Upper Permian sedimentary rocks (photographs from southern part of Gor'kovsky reservoir): (a) overturned asymmetric fold F_2; (b) thrust duplexes D_2.

splays with normal kinematics of R and R' types, which do not penetrate into Jurassic chaotic complexes. This graben belongs to the system of radial dislocations in the PK crater (Fig. 8b). All this indicates that the considered structural elements are genetically related to the Early Jurassic impact events.

Thus, the following structural assemblies are inherent for the given deformation stage: the ring crater and framing terrace, central Vorotilovo basement uplift and surrounding concentric systems of swells (compression structures), as well as normal faults and grabens (extension structures) making up radiaxial system of dislocations in the ring terrace (Fig. 8b).

This structural assembly is inseparably linked with the Lower Jurassic koptogenic complex. In the western wall of the PK structural unit, the impact breccia

Fig. 8. Structural charts. Relationships of structural assemblies in Puchezh–Katunki structural unit, based on [10, 12]: (a) nearly conformable structural assemblies of early (D_{1-2}) and late (D_4) deformation stages; (b) impact structural assemblies of stage D_3. See Fig. 3b for location. Panel (a): (*1–3*) rocks: (*1*) Upper Permian, (*2*) Mesozoic, (*3*) Lower Jurassic (koptogenic breccia); (*4*) contour lines of bottom of Middle Jurassic lacustrine sediments that fill basin; (*5*) outer contours of ring depression; (*6*) swell-like structure; (*7*) strike-slip fault and offset direction; (*8*) reverse or thrust fault; (*9*) lineation of elongation; (*10, 11*) stake number and projection of principal deformation axes on horizontal plane for early (D_{1-2}) and late (D_4) stages: (*10*) compression axis, (*11*) compression and extension axes. Additionally in panel (b): (*12*) central zones of radial troughs; (*13*) contour lines of koptogenic breccia bottom, including megablock breccia; (*14*) stake number and projection of extension axis (stage 3) on horizontal plane. Stereographic projections of dislocation poles on lower hemisphere and vectors of hanging wall offset at early deformation stages (D_{1-2}) in panel (a) and at impact stage (D_3) in panel (b). See Fig. 5 for abbreviations.



is characterized by chaotic structure. Blocks and sheets of Permian and Triassic rocks variable in size are heaped helter-skelter into a low-viscosity rubble–clay matrix, making up a megapudding structure (Figs. 9c, 9e). The koptogenic sequence is devoid of bedding but occasionally reveals pseudobedding. Indications of older folding, which predated brecciation, are noted. For example, the primary bedding is complicated by small folds, which are cut off by the irregular sides of the block (Fig. 9e). Blocks of closely cemented breccias represent a breccia-in-breccia structure.

The gradual change in orientation of the extension axis from NW to NNE along the contour of the PK depression from north to south has been established from kinematic analysis of normal–pull-apart structural elements (D_3) in area of the Gor'kovsky water reservoir (Fig. 8b, diagrams). Such a radial–concentric paleostress distribution is consistent with the location of the impact crater epicenter and the radial system of grabenlike sinks (Fig. 8b).

Structural assemblies of the fourth generation (D_4) are represented by low-amplitude reverse, reverse-strike-slip, and thrust faults, as well as various mesostructures. In Permian and Triassic sedimentary rocks, the faults of this generation crosscut and displace impact structures (D_3), for example, normal faults and clastic dikes (Figs. 9c, 9d; 5). Deformations of this stage in the Jurassic koptogenic sequence developed along local tectonic zones, expressed as the rotation of small blocks. Small clayey fragments acquire a sigmoid shape with corresponding internal foliation (Fig. 9e). Snowball structures and linear orientation of fragments are also noted.

Rotation is associated with low-amplitude thrust, reverse, and strike-slip faulting. Small asymmetric faultline folds disturb the pseudobedding along the reverse and thrust fault surfaces (Figs. 9c, 9e). A slip commonly does not exceed a few meters. Zones with numerous reverse and thrust faults impart the appearance of tectonic melange to koptogenic rocks.

Statistical analysis of gliding structures complicating koptogenic breccia shows that they formed under conditions of horizontal NNW–SSE compression (Fig. 10, diagrams III, IV). A similar orientation of the compression axis was noted in Triassic sedimentary rocks (Fig. 10, diagrams I, II).

DISCUSSION

The structural assemblies recognized in the framework of the PK depression bear attributes of a long-term that evolution resulted in four deformation stages related to different factors.

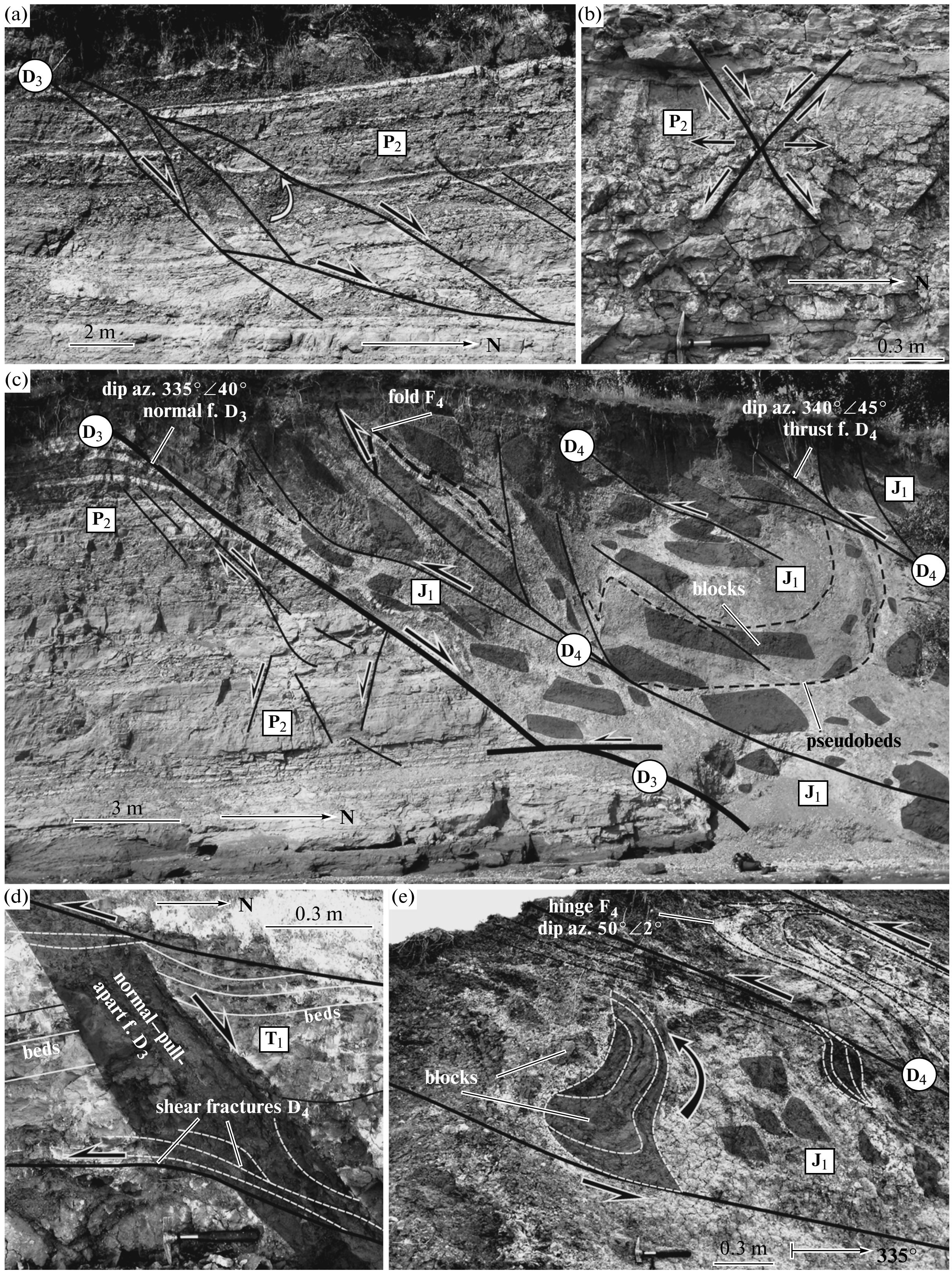
The early deformation stages (D_{1-2}) developed under conditions of horizontal compression. The first stage (D_1) was characterized by the formation of folds passing into nappes with SSE overthrusting; the second stage (D_2) evolved under transpressional conditions (shear + compression), giving rise to the formation of divergent palm structures. The axes of horizontal compression at these deformation stages are almost coaxial and oriented in the NNW–SSE direction (Fig. 8a, diagrams). This deviates by ~90° from the orientation of paleostresses related to propagation of the presumable shock wave from the epicenter of the PK crater. All this indicates that early deformations (D_{1-2}) and superposed impact transformation (D_3) are independent.

Judging from the drilling results, the tectonic dislocations of these stages involve the Archean basement and sedimentary cover from the Vendian rocks to the Upper Permian sequence (Fig. 4c). It remains unclear whether Lower Triassic sedimentary rocks participated in these dislocations; however, the Lower Jurassic rocks are obviously a sealing complex with respect to these deformations. Thus, the horizontal shortening (D_{1-2}) was superposed upon Permian rocks and predated the Lower Jurassic koptogenic and, probably, Lower Triassic sedimentary rocks. In general, this deformation can be regarded as a manifestation of the Hercynian tectonic stage.

The third deformation stage (D_3) is related to Early Jurassic impact events, when the ring crater, surrounding terrace, central Vorotilovo basement uplift, and system of radial–concentric dislocation formed as a result of a meteorite (Fig. 8b). The K–Ar age of koptogenic rocks (200–183 Ma) corresponds to the time interval when this catastrophic event took place [10]. The overlying rocks are Middle Jurassic (Bajocian–Bathonian) in age. Since the koptogenic breccia contains a Bajocian spore and pollen complex, it is suggested that the impact event could have happened in the Bajocian (164–170 Ma) and that microspores, along with water, penetrated into deep-seated rocks from the impact crater [10]. An alternative interpretation explains this phenomenon by the later migration of groundwater or hydrothermal solutions along reactivated fault systems. The Bajocian age of the impact catastrophe is refuted by the data that no mass extinction of organisms occurred at that time [38]. Therefore, to date it is more reasonable to rely on the K–Ar isotopic age of the PK impact structure.

The fourth deformation stage (D_4) developed after the impact event as a reactivation of early faults (D_{1-2}). Small offsets (a few meters) are noted along reverse, thrust and strike-slip faults in the Lower Jurassic koptogenic breccia. Because of small offsets and coaxial deformations D_{1-2} and D_4 in the Permian sedimentary rocks, young structures have been identified ambiguously.

Fig. 9. Structures of deformed Permian, Triassic and Lower Jurassic sequences: (photographs from Gor'kovsky reservoir): (a) antithetic listric normal faults (white arrow indicates direction of rotation) at stage D_3; (b) systems of conjugated X-shaped shear fractures at stage D_3; (c) normal fault (D_3) that cuts off Upper Permian sequence and controls southern wall of graben filled with koptogenic breccia (D_3), which is displaced along low-amplitude thrust faults (D_4); (d) clastic dike (normal–pull-apart fault D_3) in Lower Triassic sedimentary rock disturbed by shear fractures D_4; (e) Lower Jurassic koptogenic breccia deformed at stage D_4 (rotation of blocks, low-amplitude thrusting, fault-line minifolds). See Fig. 5 for explanation of symbols.


(a)
D3
P2
2 m
N
(b)
P2
N
0.3 m
(c)
dip az. 335° ∠40°
normal f. D3
fold F4
dip az. 340° ∠45°
thrust f. D4
D3
D4
J1
P2
J1
blocks
J1
D4
D4
P2
pseudobeds
D3
J1
3 m
N
(d)
N
0.3 m
normal–pull-apart f. D3
beds
beds
T1
shear fractures D4
(e)
hinge F4
dip az. 50° ∠2°
blocks
D4
J1
0.3 m
335°

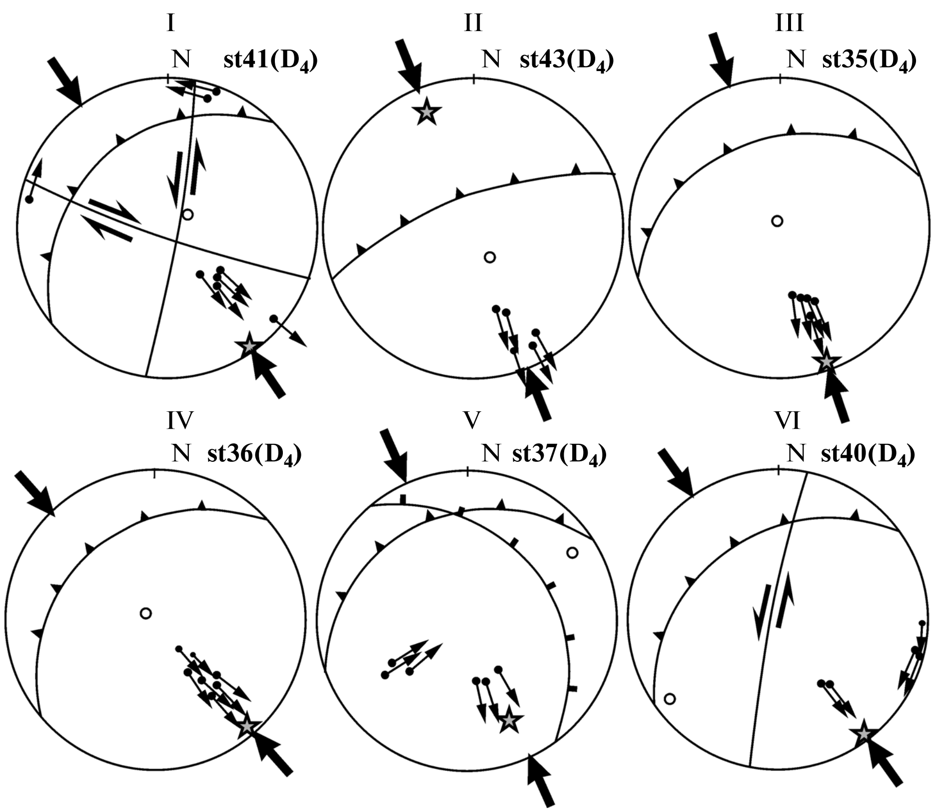


Fig. 10. Stereographic projections of fracture poles with vectors of hanging wall offset at late deformation stage D_4 on lower hemisphere: (I–II) in Triassic rocks and (III–VI) in Lower Jurassic koptogenic breccia. See Fig. 8a for location of stakes (st35–st43) and Fig. 5c for legend.

Structural assemblies similar to those of stage D_4 were noted in in Lower Triassic and Callovian rocks of the VV zone in the Vetluga and Unzha river valleys. The rejuvenation of the emergence of the Vorotilovo basement uplift at the end of the Mesozoic or later is emphasized by the domal uplift of Middle Jurassic rocks from under Lower Cretaceous sediments at the center of the PK structure (Figs. 4b, 4c). Thus, the Late Mesozoic is the lower chronological limit of this deformation stage. Taking into account that the VV zone is readily interpreted in aerial photographs and expressed in the recent topography, we can assume its certain reactivation during the neotectonic stage in agreement with new data on the adjacent Vyatka–Kazan dislocation zone [22].

Kinematic analysis of structural elements D_4 shows that they formed under conditions of horizontal compression oriented primarily in the NNW–SSE direction (Fig. 10). This trend is retained with small variation along the entire extent of the VV zone. The early fold–thrust structural units D_{1-2} developed in approximately the same geodynamic conditions. The measurements of borehole breakouts observed in the Vorotilovo Hole show that the axis of present-day maximal horizontal compression is oriented in the NW–SE direction (137° ± 15° SE) [36]. This estimate is consistent with kinematic data and serves as indirect evidence for relations of deformation D_4 to the neotectonic processes.

Dynamic interpretation. The PK structural unit is localized in the large VV zone of dislocations. The latter reveals indications of long-term evolution and periodically resuming activity beginning from formation of the Mid-Russian collisional belt in Paleoproterozoic and then during Hercynian, Kimmerian, and probably Kimmerian–Alpine tectonic cycles. The superposed structural assemblies of the Hercynian (D_{1-2}) and Kimmerian–Alpine (D_4) deformation stages in the VV zone were formed under similar dynamic conditions. This is apparently gives evidence for extremely long tectonic megacycle, which periodically resumed in the given part of the EEP.

Extending for more than 600 km, the VV zone has heterogeneous structure. In the southwest, within the PK segment, this zone forms a sigmoid bend (strike-slip compression duplex) and is distinguished by the most intense folding and faulting related to transpression (Fig. 11). To the northeast, the transpressional segment gives way to a system of disperse shear dislocations, which is emphasized by the combination of

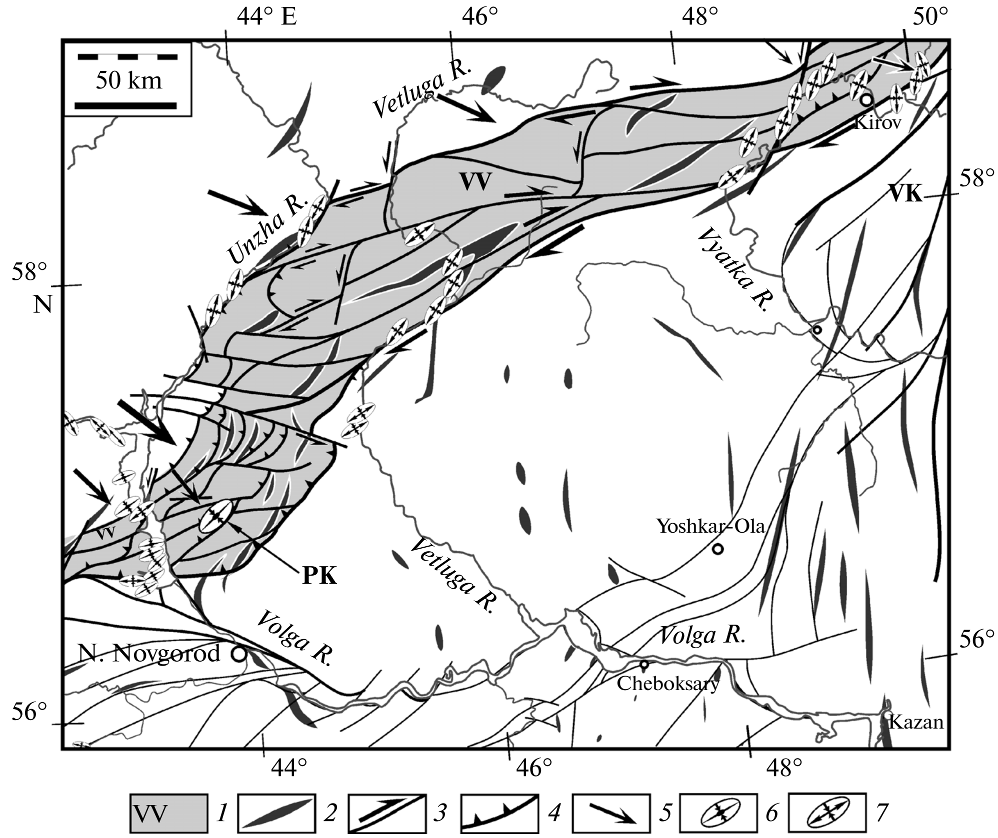


Fig. 11. Structural–kinematic schematic map of the Vladimir–Vyatka Zone. (*1*) Vladimir–Vyatka Zone; (*2*) swell-like structure; (*3, 4*) dislocations: (*3*) strike-slip fault, (*4*) reverse or thrust fault; (*5*) inferred direction of horizontal offset; (*6, 7*) near-horizontal principal deformation axes at early (D_{1-2}) and late (D_4) stages established by observations: (*6*) compression axes, (*7*) compression and extension axes). See Fig. 3 for abbreviations.

second-order master and diagonal faults oriented like synthetic (R) and antithetic (R') shears, as well as by diagonal tectonic swells (Fig. 11). This right-lateral structural pattern is consistent with the results of mesostructural observations. The kinematic analysis of dislocations in this segment of the zone shows that deformation developed here under compression along the NW–SE and NNW–SSE directions in line with right-lateral offset along the VV zone (Fig. 11).

In general, the VV zone extends parallel to the Mid-Russian dislocation zone located 200 km to the north (Fig. 1) and probably participates along with the latter in the development of the common dynamic system of offsets to the southeast [17–20]. It is also suggested that the VV zone is dynamically conjugated with the Vyatka–Kazan zone of dislocations, with which it merges in the northeast (Fig. 11).

The PK impact structure is confined to the domain of the most intense deformation in the transpressional segment of the VV zone (Fig. 11). Such a direct meteorite impact not only in the tectonic zone separating large structural domains of EEP but also in its most dynamically strained segment looks fantastic and unlikely. It should be noted that such a tectonic position is inherent to many other “astroblemes” [29], in particular, to the Kaluga and Karla structural units. Nevertheless, available evidence, including the estimated pressure of the impact effect (up to 50 GPa) and its decrease with depth, can hardly be attributed to endogenic processes [10], although such attempts are being undertaken now. In particular, the model of near-surface plasma explosion is attractive. The power of such an explosion can be great, and its localization in the strained segment of tectonic zone looks quite feasible [12].

CONCLUSIONS

(1) The PK structural unit is a result of the long-term manifestation of tectonic processes within one of the largest dislocation zones of the EEP, and probably, of a random impact event that occurred in one of the most tectonically strained segments of this zone. For now, the meteoritic factor that affected the evolution of the PK structure cannot be denied; however, the hypothesis of a near-surface plasma explosion should be kept in mind.

(2) Four deformation stages have been distinguished in the evolution of the PK structural unit: Hercynian (1) fold–nappe and (2) transpressional dislocations; (3) formation of impact crater and system of radial and concentric dislocations in Early Jurassic (200–183 Ma); (4) low-amplitude tectonic reactivation of the Hercynian faults during the Kimmerian–Alpine stage of evolution.

(3) The Vladimir–Vyatka zone controlling the PK structural unit is a long-lived zone of dislocations with predominant right-lateral offset at the plate stage of its development. The zone evolved cyclically, starting from Paleoproterozoic collisional events and finishing by the Kimmerian–Alpine stage of reactivation.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (projects nos. 13-05-00298, 14-05-00149) and the Division of Earth Sciences, Russian Academy of Sciences (program no. 10).

REFERENCES

1. A. D. Arkhangel'sky, "Structure of the Russian Platform," Byull. Mosk. O-va Ispyt. Prir., Otd. Geol. **18** (3/4), 5–39 (1940).
2. V. V. Bronguleev, *Minor Folding of Platforms* (MOIP, Moscow, 1951) [in Russian].
3. R. N. Valeev, *Tectonics of the Volga–Ural Interfluve* (Nedra, Moscow, 1968) [in Russian].
4. R. N. Valeev, "The East European Platform," in *Faults and Horizontal Movements in Platform Regions of the USSR* (Nauka, Moscow, 1977), pp. 48–64 [in Russian].
5. R. N. Valeev, *Aulacogens of the East European Platform* (Nedra, Moscow, 1978) [in Russian].
6. L. A. Vardanyants, "An explosion pipe in the central Russian Platform," Izv. Akad. Nauk Armenian SSR **14** (2), 57–62 (1961).
7. *Geology of the USSR, Vol. XI: Volga and Kama Regions. Part 1: Geological Description*, Ed. by K. R. Chepikov (1967) [in Russian].
8. *Hypsometric Map of the Crystalline Basement Surface in Central and Northern Parts of the East European Platform on a Scale of 1 : 2500000*, Ed. by V. P. Orlov and D. L. Fedorov (VSEGEI, St. Petersburg, 2001) [in Russian].
9. *Deep Structure, Evolution and Mineral Resources of Early Precambrian Basement of the East European Platform: Interpretation of Data on 1-EU Reference Profile, 4B and TATSEIS Profiles*, Ed. by A. F. Morozov (GEOKART–GEOS, Moscow, 2010), Vol. 2 [in Russian].
10. *Deep Drilling in the Puchezh–Katunki Impact Structure*, Ed. by V. L. Masaitis and L. A. Pevzner (VSEGEI, St. Petersburg, 1999) [in Russian].
11. G. I. Goretsky, "Insights into the Puchezh–Balakhna dislocations: Manifestations of injection tectonics in the Russian Platform," Byull. Mosk. O-va Ispyt. Prir., Otd. Geol. **37** (5), 80–110 (1962).
12. *State Geological Map of the Russian Federation on a Scale of 1 : 1000000 (New Series), Map Sheet O-37, (38), Nizhni Novgorod. Explanatory Notes*, Ed. by V. P. Kirikov (VSEGEI, St. Petersburg, 2000) [in Russian].
13. State Geological Map of the Russian Federation on a Scale of 1 : 1000000 (New Series), Map Sheet O-37, (39), Explanatory Notes, Ed. by V. P. Kirikov (VSEGEI, St. Petersburg, 1999) [in Russian].
14. Yu. V. Kazantsev and T. T. Kazantseva, *Structural Geology of the Southeastern East European Platform* (Gilem, Ufa, 2001) [in Russian].
15. M. A. Kamaletdinov, V. A. Stepanov, I. M. Zhukov, et al., *Thrust–Nappe Tectonics of the Volga–Ural Region* (Moscow, Nauka, 1990).
16. S. Yu. Kolodyazhny, *Structural–Kinematic Evolution of the Southeastern Baltic Shield in Paleoproterozoic* (GEOS, Moscow, 2006) [in Russian].
17. S. Yu. Kolodyazhny, "Structural and kinematic assemblies in sedimentary rocks of the Phanerozoic cover of the Mid-Russian Dislocation Zone," Geotectonics **44** (2), 139–157 (2010).
18. S. Yu. Kolodyazhny, "Structures of lateral flow in the northeastern East European Platform. Paper 1: Geological structure and structural assemblies of basement," Byull. Mosk. O-va Ispyt. Prir., Otd. Geol. **87** (1), 15–24 (2012).
19. S. Yu. Kolodyazhny, "Structures of lateral flow in the northeastern East European Platform. Paper 2: Geological structure and structural assemblies of sedimentary cover," Byull. Mosk. O-va Ispyt. Prir., Otd. Geol. **87** (2), 3–16 (2012).
20. S. Yu. Kolodyazhny, D. S. Zykov, and M. G. Leonov, "Structural–kinematic parageneses of the basement and cover at the southeastern margin of the Baltic Shield," Geotectonics **41** (6), 423–439 (2007).
21. M. L. Kopp, *Mobilistic Neotectonics of Platforms in Southeastern Europe* (Nauka, Moscow, 2005) [in Russian].
22. M. L. Kopp, "The Vyatka deformations in the East European Platform: Formation dynamics and expression in recent structure," Geotectonics **46** (6), 435–454 (2012).
23. V. A. Lobov and I. Kh. Kaveev, "Some aspects of thrust dislocations in the Volga–Ural province," in *Geology, Exploitation of Petroleum Fields, Physics and Hydrodynamics of Bed* (Kazan, 1975), pp. 27–33 [in Russian].
24. A. V. Luk'yanov, *Structural Manifestations of Horizontal Movements in the Earth's Crust* (Nauka, Moscow, 1965) [in Russian].
25. A. A. Marakushev, O. S. Bogatyrev, A. D. Fenogenov, et al., "Formation of the Puchezh–Katunkii ring structure in the Russian Platform," Dokl. Ross. Akad. Nauk **328** (3), 364–368 (1993).
26. E. V. Milanovsky, *Geological Essay of the Middle and Lower Volga Region* (Gostoptekhizdat, Moscow, 1940) [in Russian].
27. E. E. Milanovsky, *Geology of the USSR, Part 1: Ancient Platforms and Metaplatform Regions* (Moscow State Univ., Moscow, 1987) [in Russian].
28. S. K. Nechitailo, M. M. Veselovskaya, and E. N. Skvortsova, *Proceedings on Geology of the Goro-*

dets–Kovernino Tectonic Zone (Gostoptekhizdat, Moscow, 1959) [in Russian].

29. E. G. Peskov, "Belts of explosion structures ("astroblemes")," Geotektonika **26** (5), 20–26 (1992).
30. V. K. Solov'ev, *State Geological Map of the USSR on a Scale of 1 : 1000000. Map Sheet O-38 (Gor'kii)* (Gosgeoltekhizdat, Moscow, 1958) [in Russian].
31. *Structural Map of Roof of the Vereya Horizon, Moscovian Stage, Middle Series, Carboniferous System in the East European Platform*, Ed. by V. V. Bronguleev (Nedra, Moscow, 1986) [in Russian].
32. V. A. Trofimov, "Structures of horizontal compression in Tatarstan and northern Orenburg oblast," Dokl. Ross. Akad. Nauk **329** (4), 476–479 (1993).
33. R. R. Tumanov, "New data on structure of the Gorodets–Kovernino tectonic zone," in *Proceedings on Geology of the Eastern Russian Platform* (Kazan State Univ., Kazan, 1973), Issue 5, pp. 112–125 [in Russian].
34. L. V. Firsov, "On meteoritic origin of the Puchezh–Katunki crater," Geotektonika **1** (2), 106–118 (1965).
35. V. G. Chuvardinsky, *Quaternary Period: A New Geological Concept* (Kola Sci. Center, Russian Acad. Sci., Apatity, 2012) [in Russian].
36. K. Huber, K. Fuchs, J. Palmer, et al., "Analysis of borehole televiewer measurements in the Vorotilovo Drillhole, Russia: first results," Tectonophysics **275** (1/3), 261–272 (1997).
37. R. A. Marrett and R. W. Allmendinger, "Kinematic analysis of fault-slip data," J. Struct. Geol. **12**, 973–986 (1990).
38. J. Palfy, "Did the Puchezh–Katunki impact trigger an extinction?," in *Cratering in Marine Environments and on Ice*, Ed. by H. Dypvik (Springer, Berlin, 2004), pp. 135–148.

Reviewers: T.N. Kheraskova and M.A. Goncharov

Translated by V. Popov