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In fond memory of my late teacher Boris Alekseevich Ivanov

Shear Structural Paragenesis and Its Role in Continental Rifting of the East Asian Margin

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Abstract—The spatial–genetic relationships between transit fault systems of the East Asian global shear zone (EAGSZ) are analyzed. It is established that the EAGSZ internal structure between the Okhotsk and South China seas is identical to that of world-known natural and experimental shear zones, which confirms its development as an integral structure. The structural–kinematic analysis included the Tan-Lu–Sikhote-Alin (TS) system of left-lateral strike-slip faults (NNE 25°–30°) and the Bohai–Amur (BA) system of updip–strike-slip faults (NE 50°–70°). It is shown that these systems were formed as structural parageneses during two stages. The first and shear–thrust stage (Jurassic–Early Cretaceous) was marked by general NNW-oriented compression with the formation of the TS system of left-lateral strike-slip faults and their structural parageneses (compression structures) such as the BA system of updip–thrusts. The second, strike-slip–pull apart stage (Late Cretaceous–Cenozoic) was characterized by SE-directed tangential compression, which was generated by the SW left-lateral displacement of the continental crust along the Central Sikhote-Alin deep-seated fault. In such dynamic settings, the updip–thrust kinematics of the BA system gave way to that of left-lateral strike-slip faults. The strike-slip faults were formed in the transtension regime (shear with extension), which determined the development of pull-apart structures, where the left-lateral shear extension component played the decisive role. Simultaneously, the extension involved the Tan-Lu strike-slip fault with the formation of the rift valley and the discrete development of sedimentary basins along the latter.

Keywords: strike-slip faults, structural parageneses, structuring dynamics, structural–dynamic stages, sedimentary basins, rifting, Far East

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INTRODUCTION

In the Late Mesozoic–Cenozoic, the continental crust of the East Asian margin was subjected to extensive riftogenic destruction. The revelation of the rifting nature represents the first-priority scientific task. The structure and geodynamic regime of its formation are the main criteria for the recognition of rifts. Other features such as the composition of the rift-filling rocks, the manifestation and type of magmatism, and others that are frequently readily recognizable are also important, although secondary in significance relative to the structural features and, which is most important, too changeable to serve as a criterion for recognizing rifts [18].

The riftogenic destruction of the crust beneath the eastern margin of the Asian continent is primarily reflected in the formation of many grabens that controlled development of sedimentary basins (SB). Their origin was traditionally explained by fault tectonics. In the terminal 1970s, a new view on their nature was formulated, according to which the eastern margin of Asia evolved in the Mesozoic–Cenozoic in shear geodynamic settings in response to the lateral displacement of the Asian continent and/or Pacific oceanic plate with the formation of the East Asian global shear system (EAGSZ) in their junction zone [38, 39, and others]. When considering the EAGSZ's development [40, 42, 44–46, 48, and others], the researchers analyzed together systems of transit NNE-trending strike-slip faults defined in [6, 11, 12, and others], the East Asian volcano-plutonic belt of marginal seas, and the marginal continental sedimentary basins united into the East Asian graben belt [4 and others]. These investigations revealed a particular type of crustal destruction, the so-called pull-apart extension structures, which developed discretely under lateral compression of the lithosphere along strike-slip faults as their duplexes, which corresponds to the subsequently formulated notion: strike-slip fault development in the transtension regime (shear with extension) [17].

The analysis of strike-slip faults, together with extension structures, made it possible to explain both the spatial and genetic relations with transit strike-slip faults of volcanic and graben belts: in the first case, pull-apart extension structures played the role of magma conduits and, in the second one, initiated the subsidence along normal faults with the formation of grabens. This concept served as a basis for the structural analysis of several Cenozoic coaliferous basins in the Primorye region [41, 43–46, and others]. It was established that these basins are located along NNE-extending strike-slip faults and correspond by their position and morphology to sedimentary basins, which were known at that time under different names: open fractures (A.V. Luk'yanov), basins of strike-slip extension (V.S. Burtman), and amygdaloid structures (N.A. Florensova and V.P. Solonenko). In the foreign geological literature, such basins associated with strike-slip faults are termed as pull-apart basins (B. Birchall), where the shear component of extension played a decisive role. The conclusion on the development of coaliferous basins in the Primorye region above strike-slip extension areas of the basement explained several phenomena: the origin of normal faults with the formation of depressions favorable for the accumulation of plant material; the intermittent manifestations of different-depth volcanism in basins; and the elevated mineralization exceeding the clarke values by tens to hundreds of times, which forms locally autonomous deposits of, for example, germanium. It was also suggested that the endogenic factor in coaliferous sedimentary basins probably played a significant role also at the early stages of the coal formation. Several factors could be responsible for this process: (1) the deep heat flow, which provided conditions for relatively stable local warming; (2) the intermittent eruptions, which supplied fertile ash; and (3) the permanent circulation of high-temperature thermal solutions enriched with trace elements, which stimulated the vegetation growth. These conditions could guarantee the prolonged existence of particular oases with the accumulation of plant remains in depressions, which continued forming. At the later stages, the deep heat flow stimulated the coalification of plant remains, gas generation from coals, and the formation of coking coal [41, 43, 44].

It is recently established that practically all the continental rifts were formed with the contribution of the shear component [27 and others]. As is shown, strike-slip tectonics play a significant role in the formation of both the conditions favorable for coal accumulation in closed basins and conduits for the influx of deep, primarily, hydrocarbon (HC) fluids. This discovery substantially clarified many aspects in the development of petroliferous basins. The observations gained during last decades, which point to the significant contribution of strike-slip tectonics to the extension of the crust, confirm our inferences concerning the dynamics of the marginal continental rifting in the eastern Asian margin in strike-slip geodynamic settings. This work is dedicated to the analysis of the geochronological relations between the geodynamic formation environments of the Late Mesozoic–Cenozoic sedimentary basins that developed along regional strike-slip faults as their structural parageneses. It involves the central part of the East Asian global shear zone between the Okhotsk and South China seas with the Tan-Lu and Central Sikhote-Alin left-lateral strike-slip faults, which are the largest such structures in the Asian margin (Fig. 1).

METHODS AND APPROACHES TO THE PROBLEM's SOLUTION AND THE SOURCE MATERIALS

It is known that the dynamics, the essence of which consists in directed stress's influence on a certain geological space, are primarily reflected in the natural combinations of tectonic structures or the structural parageneses determined by compression [20 and others]. The methods of the paragenetic structural analysis, the main purpose of which is interpretation of the local and regional geodynamic regimes, are continuously improved and widely used in investigations by Russian and foreign geologists [3, 20, 24, 26, 34, 40, 55, 56, 58, 62, 72–74, and others]. One of their modifications was used for the investigation of the geodynamics of the magma- and ore-controlling structures in the Primorye region exemplified by the volumetric structures of many deposits and ore districts [40, 46]. These investigations revealed the structural–kinematic ensembles and mechanisms of tectonic movements characterizing the dominant strike-slip dislocations that determined the structures of ore deposits, as well as the dynamic–kinematic mineralization and magmatism environments.

The formation mechanism of basins associated with strike-slip faults and the related aspects of the sedimentation in them are discussed in many foreign and Russian publications. Summarized data on a wide spectrum of SB formation problems are available, for example, in [27, 61, and others]. The main purpose of this work is the recognition of the structural–kinematic ensembles formed by the paragenetic development of regional chaotically oriented fault systems that control sedimentary basins with the analysis of the changes in their kinematic characteristics in response to changes in the directions of the regional compression vectors. The megastructures (regional faults) were investigated together with the analysis of the mesostructures (sedimentary basins) controlled by them. The analysis involved the morphology, the internal structural features, and the local dynamic–kinematic formation environments of the sedimentary basins, as well as the regularities of their localization along regional faults. Taking into consideration the fact that the Cretaceous–Early Paleogene ore deposits of Sikhote-Alin were formed prior to and simultaneously

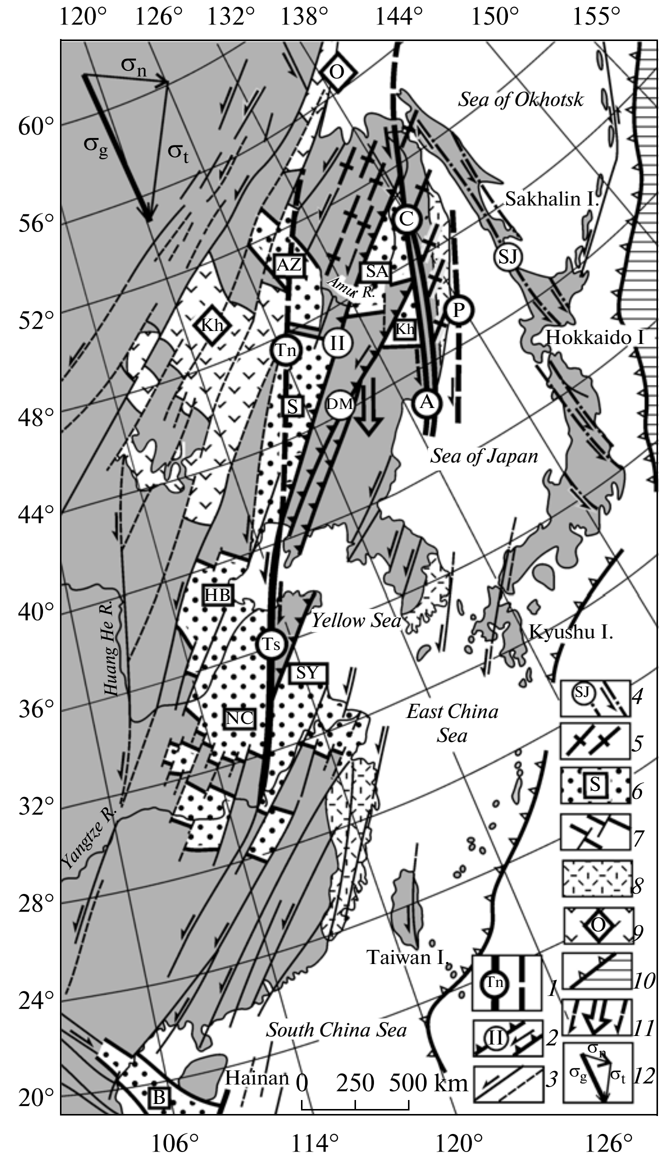

Fig. 1. Schematic structural and dynamic–kinematic development environments of the East Asian global shear zone and its constituting systems of transit faults (compiled using materials from [7, 12, 45, 65, 75, 77, and others]).

(*1*) Principal left-lateral strike-slip faults of the Tan-Lu–Sikhote-Alin (TS) longitudinal system (the dashed line shows overlain structures): Tan-Lu, southern (Ts) and northern (Tn) segments; Central Sikhote-Alin (C), Arsenyev (A), (P) Pribrezhnyi; (*2*) principal updip–strike-slip faults of the Bohai–Amur (BA) system: Ilan–Itun (II), Dunhua–Mishan (DM); (*3*) left-lateral strike-slip faults, updip–strike-slip faults (the dashed line show the assumed structures) of the near-continental diagonal system; (*4*) Sakhalin–Japan (SJ) zone of strike-slip faults of the near-continental diagonal system; (*5*) Sikhote-Alin imbricate–fold system, (*6*) sedimentary basins: Sunlyao (S), Middle Amur (MA), North China (NC), Subei–Yellow Sea (SY), Bak-Bo (B), Khanka (Kh), Amur–Zeya (AZ) and their generalized boundaries (*7*); (*8*) Cretaceous–Cenozoic volcanics of the East Asian belt; (*9*) Late Jurassic–Early Cretaceous volcanics of the Okhotsk–Khingan belt and its segments: (O) Okhotsk, (Kh) Khingan; (*10*) Benioff zone (the oceanic crust is hachured); (*11*) direction of the assumed displacement of the crustal block with the synchronous low-amplitude right-lateral (Tan-Lu fault) and left-lateral (Arsenyev) strike-slip faults; (*12*) direction of the general (initiative) compression of the lithosphere (σ) and its derivatives: (t) tangential, (n) normal.

with the Late Mesozoic–Cenozoic stage in the development of the sedimentary basins, their defined dynamic–kinematic structural features were used for solving the formation problems of the sedimentary basins. For example, it is established that the ore deposits are distributed along NNE-trending left-lateral strike-slip faults being discretely localized in areas with strike-slip extension structures that control ore bodies. Their closely arranged groups are frequently distributed in an en echelon manner with the formation of extension duplexes, which exhibit configuration (elongated rhombs) similar to that of most known strike-slip pull-apart basins that were formed in conjugation zones of noncoaxial strike-slip faults. This example of morphological-kinematic similarity confirms the genetic relations between the development of sedimentary basins (fault-associated subsidence) and the underlying extension structures in the basement. Some other factors, which are discussed below and interpreted here in a manner differing from the traditional views, were also taken into consideration.

The formation of sedimentary basins was likely stimulated by the dispersed brittle crustal extension in the form of strike-slip local zones of anomalous fracturing rather than by through extension structures as during the formation of ore bodies and dikes. Such zones of anomalous fracturing, on the one hand, initiated fault-associated subsidence and, on the other, were unfavorable for magma's migration toward the surface. The latter explains the fact that sedimentary basins are mostly filled with sedimentary formations. At the same time, the structures of dispersed crustal extension could play role of conduits for highly mobile hydrothermal fluids and, moreover, the Earth's degassing and deep heat flow. Such structures correspond to subvertical mantle-reaching fluid-saturated columns with elevated fracturing up to 20 km in diameter, which were recently discovered by magnetotelluric sounding methods. In this connection, noteworthy are microdislocations in strike-slip fault zones as well. It is established that general transpression stimulates the development of tectonic strains in strike-slip fault zones, which enhance the migratory ability of the gas–liquid phase [10, 31, and others]. In such dynamic environments, the formerly disordered space acquires a regular orientation and the conduits become uniformly elongated to facilitate the fluid migration despite the general porosity's decrease [19].

High-amplitude displacements of the crust along strike-slip faults imply that development of different-depth subhorizontal detachments with adequate displacement amplitudes. This primarily concerned the asthenosphere representing a layer with lowered viscosity, which underlies the lithosphere being formed in the upper mantle. Intracrustal detachment zones are recorded at different levels reflecting the tectonic layering of the crust resulting from its differentiated displacements. When reaching the surface, the detachment zones form systems of listric thrusts with oblique orientation, which points to their associations with strike-slip faults as their compression duplexes. There are grounds to assume that the upper crustal extension structures associated with strike-slip faults and independent of deep magma sources were formed in the upper layers of the crust involved into subhorizontal syn-shear displacements. Such a situation may also explain the scant magmatism in sedimentary basins or even its absence.

The internal structure of the lower parts in sedimentary basins with maximal normal faulting determined by extension in the basement is most informative with respect to the basement geodynamics. Higher in the section, normal faults become gradually less expressed and are overlain by sediments. This stage of general subsidence with the significant expansion of the basin is usually considered as the postrifting one, which is, in my opinion, unreasonable in some situations. There are grounds to assume that the gradual upward disappearance of normal faults is explained by the progressively weakened influence of extension forces on the moving-away upper layers of the growing sedimentary cover of basins in response to the basement's subsidence rather than by their cessation in the latter (rifting termination). In such a situation, the differentiated descending displacement along normal faults graded into the general plicative downwarping of sedimentary complexes that were formed under the influence of the continuing crust extension and its consequences: deep heat and fluid flows and the Earth's degassing. Due to both the increase in the size of the basement extension areas and their subsidence, the sedimentary basins also progressively widened. Episodic manifestations of volcanism (primarily, Neogene–Quaternary basite) within sedimentary basins serve as the confirmation of rifting at the later stages of their development as well.

The genetic succession of almost coeval cause-and-effect relations (strike-slip fault activation–local shear extension of the basement–subsidence along normal faults with the formation of sedimentary basins) allows the paleontologically dated sedimentary complexes to be used for assessing the age of the strike-slip fault activation episodes. It is assumed that the maximal thickness of the sedimentary sequence reflects the time of the most significant strike-slip displacements, which provided adequate extension in the basement and, consequently, the rapid subsidence of the sedimentary basin. In this connection, the age of the magmatism manifestations in the sedimentary basins and the consequences of the significant syn-shear basement extensions are taken into consideration as well.

The analysis of the published data of foreign and Russian researchers was applied for solving these problems. Ivanov [11, 12] was the first to discover and describe the Central Sikhote-Alin left-lateral strike–slip fault, the largest fracture on the eastern Asian margin. He also formulated the concept of the Sikhote-Alin strike-slip tectonics, which stimulated investigations in this direction. They resulted in the discovery of a system of left-lateral strike-slip faults subparallel or parallel to the Central Sikhote-Alin strike-slip fault [38]. The system of left-lateral Tan-Lu faults was primarily investigated by Chinese scientists [75, 77, and others]. The comprehensive characteristics of the structure and development of the Sunlyao, Tanyuan, Huabei–Bohaiwan, Subei–Yellow Sea, Middle Amur, and Amur–Zeya sedimentary basins are available in [5, 14–16, 21–25, 37, 66–68, 78–80, and others]. The years-long investigations of the Middle Amur sedimentary basin culminated in a monographic description accomplished by a mixture of authors [28]. Small-scale geological and tectonic maps were also used [7, 65, and others].

MORPHOLOGICAL–KINEMATIC CHARACTERISTIC OF THE REGIONAL FAULTS AND THEIR DEVELOPMENT AS STRUCTURAL PARAGENESES

Three transit fault systems, which constitute the East Asian global shear zone and are particularly distinct in the area between the Okhotsk and South China seas, are dominant in the Asian margin (Fig. 1). One of these systems (longitudinal) is oriented parallel to the Asian margin (NNE 25°–30°) and two others (diagonal), obliquely to the latter being represented by the near-continental (NE 50°–70°) and near-oceanic (meridional) systems. The fourth (transverse) system of the WNW strike is well expressed between the transit faults. All the above systems reflect the main features of the EAGSZ's internal structure, which is identical to that of the world-known natural shear zones repeatedly reproduced experimentally beginning from the experiments by Cloos [62]; Riedel [73]; and, subsequently, by [34, 36, 55–57, and others]. According to these data, differently oriented fractures are formed asynchronously, which provides grounds to consider the fault systems of the East Asian global shear zone as illustrating the successive development of a single integral shear zone. The probable interrelated genesis and geochronological correlation of the diagonal and longitudinal transit EAGSZ faults have never been analyzed. At the same time, the EAGSZ's development in the strike-slip regime as an integral structure implies paragenetic relations between its constituting fault systems. In this work, the main attention is paid to the study of the structural ensemble consisting of the conjugate Tan-Lu–Sikhote-Alin (TS) and Bohai–Amur (BA) systems (Fig. 1).

The Tan-Lu–Sikhote-Alin system, which occupies the central position in the East Asian global shear zone, is represented primarily by the Tan-Lu (TL) and Central Sikhote-Alin (CSA) deep-seated faults. These fractures oriented in the NNE (25°–30°) direction are the largest left-lateral strike-slip faults within the Asian margin (Fig. 1). This system also includes the Ussuri and Arsenyev strike-slip faults and similar structures of the East Sikhote-Alin strike-slip zone located between the Central Sikhote-Alin and Pribrezhnyi deep-seated faults (Fig. 2). The Tan-Lu (southern segment) and Ilan–Itun faults (II) (Fig. 1) form an S-shaped structure (Fig. 3), which is considered as a single strike-slip fault [75, 77, and others]. At the same time, the Tan-Lu strike-slip fault differs from its Ilan–Itun counterpart by both the orientation and substantially higher amplitude of the left-lateral displacements, as well as by the synchronous kinematics (and displacements along the Tan-Lu strike-slip fault were accompanied by upward movements along the Ilan–Itun fracture). This allows the S-shaped structure to be considered as consisting of conjugate transregional faults of the Tan-Lu–Sikhote-Alin and Bohai–Amur systems, which developed in paragenetic relations.

The Tan-Lu strike-slip fault (southern segment) experienced a two-stage development history [75, 77]: (1) the Late Jurassic–Early Cretaceous marked by the high-amplitude (700–800 km) left-lateral displacement; (2) the terminal Early Cretaceous–Cenozoic, when the fault was developing as an extension structure with the formation of the rift valley 40–60 km wide (with a maximum of 80 km). In the Cenozoic, the second stage was characterized by intermittent low-amplitude right-lateral strike-slip movements against the background of the TL development mainly as an extension structure. The Late Quaternary right-lateral displacements along the TL strike-slip fault were synchronous (historical earthquakes) with the activation of left-lateral movements along the southern segment of the Arsenyev fault in the Sikhote-Alin region [47]. The synchronism of the left- and right-lateral displacements is explained by the southwestward displacement of the crustal block bordered by these faults (Fig. 1), which is confirmed by the Late Quaternary right-lateral movements along the faults bounding the TL trough in the east [58]. These movements point to the activation of right-lateral movements in the eastern crustal block. It seems that episodes of Cenozoic right-lateral displacements along the Tan-Lu strike-slip fault resulted from the southwestward displacement of crustal blocks along the Sikhote-Alin transit faults. Dissimilar to the Tan-Lu system, their left-lateral strike-slip kinematics played the decisive role also in the Late Cretaceous-Cenozoic.

The formation of the Huabei–Bohaiwan and Subei–Yellow Sea sedimentary basins adjoining the Tan-Lu strike-slip fault in the Mesozoic–Cenozoic (mainly, in the Paleogene) confirms the dominant development of the latter at the second stage as an extension structure (Fig. 3). Their main peculiar structural feature consisting in the development of half-grabens filled mainly with Paleogene sediments up to 7–8 km thick is readily distinguishable in sections across the sedimentary basins. The mirror stepped normal faults bordering half-grabens dip toward the Tan-Lu rift pointing to its parental role as an extension structure. The S-shaped configuration of this rift implies its opening in response to the activation of left-lateral movements along the faults of the Bohai–Amur system (Fig. 3). North of the Tan-Lu fault's junction with the faults of the Bohai–Amur system, there is the Sunlyao sedimentary basin (Figs. 1, 3). Its NNE-oriented extended grabens and linear mantle asthenoliths (Fig. 4) allow the conclusion that the Tan-Lu deep-seated fault continues in the Sunlyao basin's basement. The linear grabens of the Amur–Zeya sedimentary basin, which practically continues in the NNE direction the Sunlyao basin, are characterized by similar orientation (Fig. 1).

Thus, there are grounds to believe that the Tan-Lu (southern segment) continues in the NNE direction (northern segment) controlling the formation of the Sunlyao sedimentary basin (Fig. 1). At the same time, the left-lateral displacements for hundreds of kilometers established in the TL's southern segment have no reflection in its northern segment: the northern boundary of the Sino-Korean craton remained practically undisplaced along the TL strike-slip fault system. It was noted [75, 77] that the terminal part of the latter (southern segment) is complicated by the development of thrusts or overthrusts oriented obliquely to the strike-slip fault (Fig. 3), which suggests that the strike-slip faults on the flanks of the TL system are transformed into overthrust–thrust displacements. This assumption is confirmed by the paragentic synchronism of the Jurassic–Early Cretaceous left-lateral displacements along the Tan-Lu and Bohai-Amur diagonal fault system that developed in the compression duplex regime of left-lateral displacements along the TL fault at that time. The compression duplex was formed as a system of updip-thrusts that cross the craton and synsedimentary fold–thrust slices of Jurassic–Lower Cretaceous sedimentary complexes east of the craton (Fig. 2). The listric morphology of the slices with the planes flattened in the NW direction and the SE fold vergence likely reflects the cropping out of the syn-shear intracrustal subhorizontal detachments presumably with significant displacement amplitudes. The duplexes are approximately 400 km wide (Fig. 2). It is assumed that the system of spatially scattered listric thrusts and the associated formation of the imbricate structure with strongly compressed folds (strike-slip related orogenesis) reduced by the Late Creta-

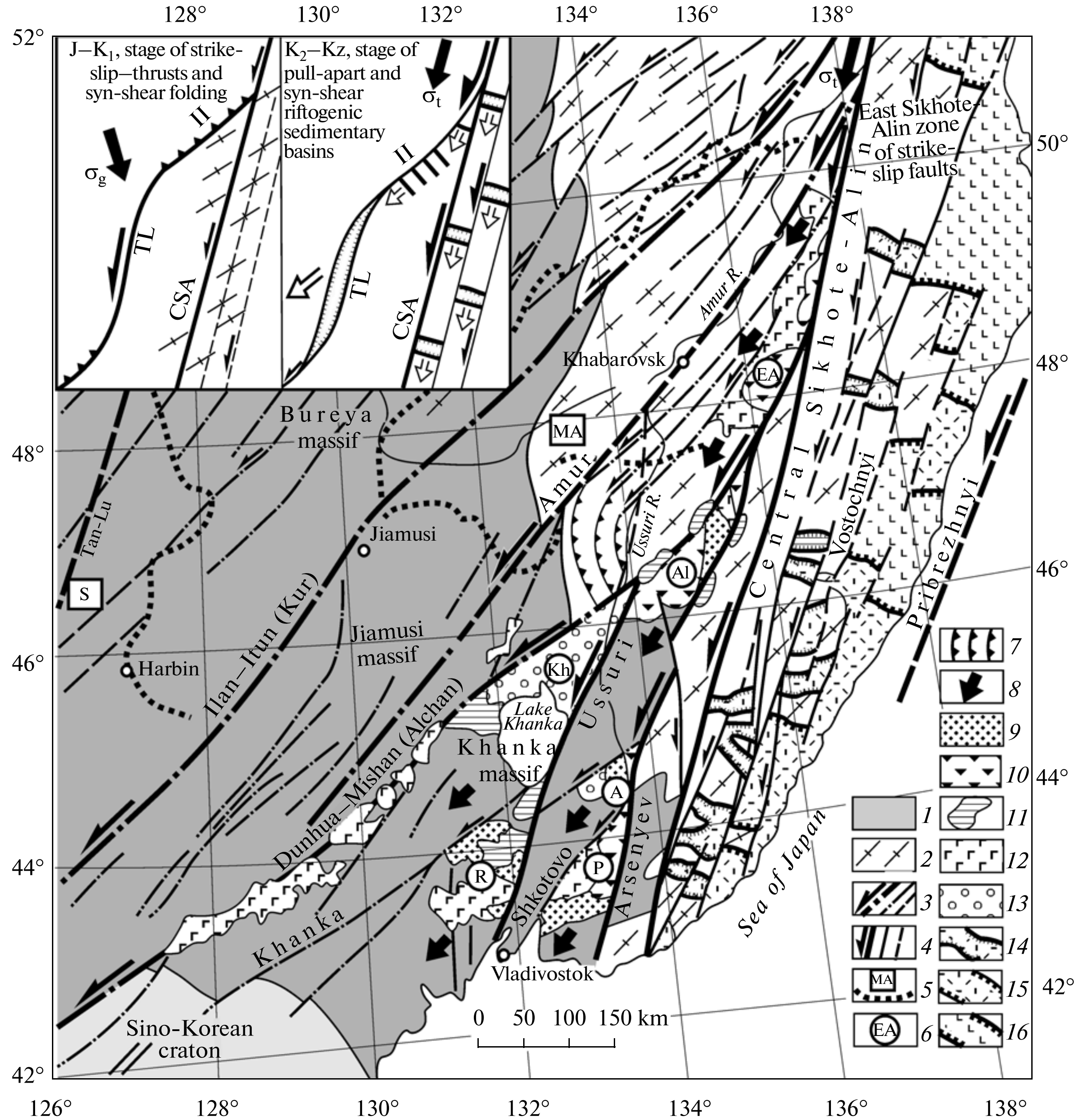

Fig. 2. Schematic structural–kinematic map of the junction zone between the Bohai–Amur and Sikhote-Alin systems of left-lateral strike-slip faults (compiled using materials from [7, 12, 38, 42, 44–46, 65, and others]).

(*1*) The Archean–Proterozoic composite craton (the Bureya, Jiamusi, and Khanka massifs) and the Sino-Korean craton intruded mainly by Paleozoic granitoids and locally overlain by Phanerozoic subplatform deposits; (*2*) Sikhote-Alin imbricate–fold system; (*3*) Bohai–Amur system of left-lateral updip–strike-slip faults: the secondary ones are designated by thin lines and the assumed or overlain ones are shown by dashed lines; (*4*) Sikhote-Alin left-lateral updip–strike-slip faults: the secondary ones are designated by thin lines and the assumed or overlain ones are shown by dashed lines; (*5*) boundaries of the Late Cretaceous–Cenozoic riftogenic sedimentary basins: Middle Amur (MA), Sunlyao (S); (*6*) Cretaceous–Cenozoic wedge-shaped extension structures: East Amur (EA), Alchan (Al), Partizansk–Sukhoi Dol (PS), Arsenyev (A), Khanka (Kh), Razdolnoe (R); (*7*) Nadan'khada imbricate–thrust frontal compression structure; (*8–13*) direction of the extension in the wedge-shaped structures (*8*) and their compensating deposits: uppermost Lower–Upper Cretaceous sediments (*9*) and volcanics (*10*), Cenozoic sediments (*11*) and basalts (*12*), Pleistocene–Quaternary sediments (*13*); (*14–16*) East Sikhote-Alin volcano-plutonic belt: Cenomanian–Paleocene volcanic structures (root levels of the volcanic cover [50]) of the syn-shear extension (*14*), generalized boundaries of the zones of syn-shear brittle crustal extension providing conditions for the development of the Late Cretaceous acid and intermediate volcanism (*15*) and the superposed Cenozoic basaltoid volcanism (*16*). Insets: schematic dynamic–kinematic settings for the step-by-step development of the transregional structural paragenesis. (σ_g) the direction of the general (initiative) compression and its derivative (tangential relative to the Central Sikhote-Alin left-lateral strike-slip fault) (σ_t; main faults of the paragenesis: Tan-Lu (TL), Central Sikhote-Alin (CSA), Ilan–Ituun (II); the open arrows designate the directions of the syn-shear extensions.

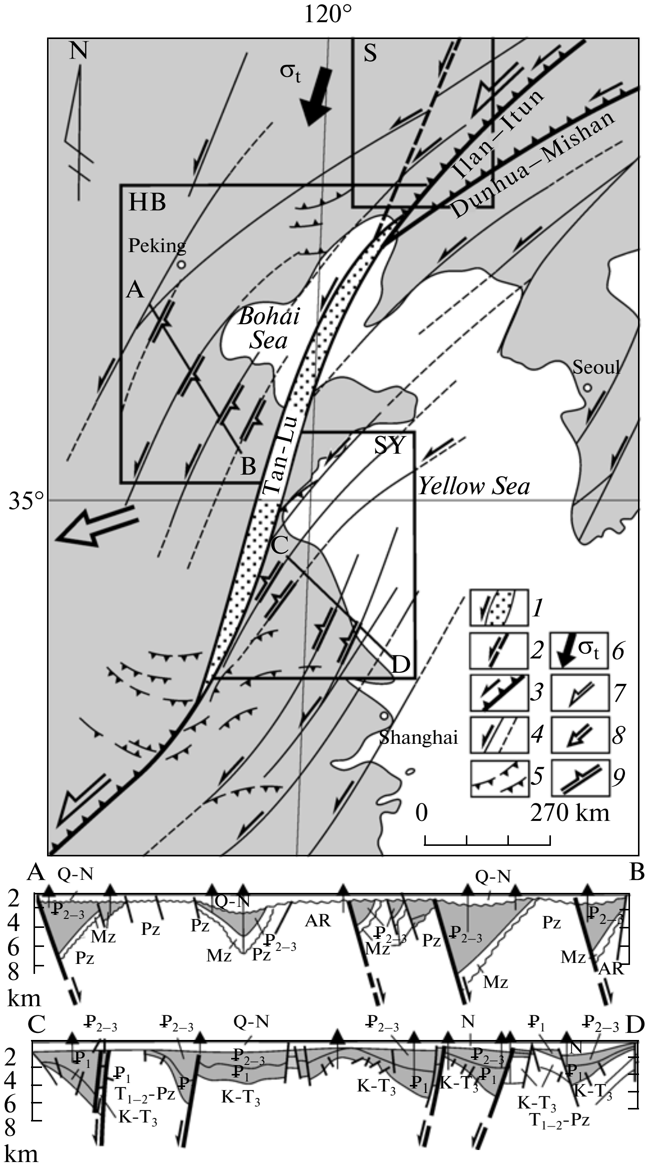

Fig. 3. Schematic dynamic–kinematic settings for the transformation of the Tan-Lu strike-slip fault into an extension structure (compiled using the materials from [75, 77–79, and others]).

(*1*) Tan-Lu left-lateral strike-slip fault transformed into the extension structure at the second development stage; (*2*) continuation of the Tan-Lu fault (northern segment) in the basement of the Sunlyao sedimentary basin (S); (*3*) principal updip–thrusts of the Bohai–Amur system; (*4*) other strike-slip faults of the Bohai–Amur system transformed into normal faults in the extension zone; (*5*) overthrust–thrust systems formed on flanks of the Tan-Lu strike-slip fault (after [75, 77]); (*6–9*) dynamic–kinematic setting responsible for extension in the Tan-Lu fault zone with the formation of the Huabei–Bohaiwan (HB) and Subei–Yellow Sea (SY) sedimentary basins: tangential compression (*6*), left-lateral strike-slip faults (*7*), direction of the extension forces (*8*), stepped normal faults directed toward the Tan-Ly fault (*9*, sections).

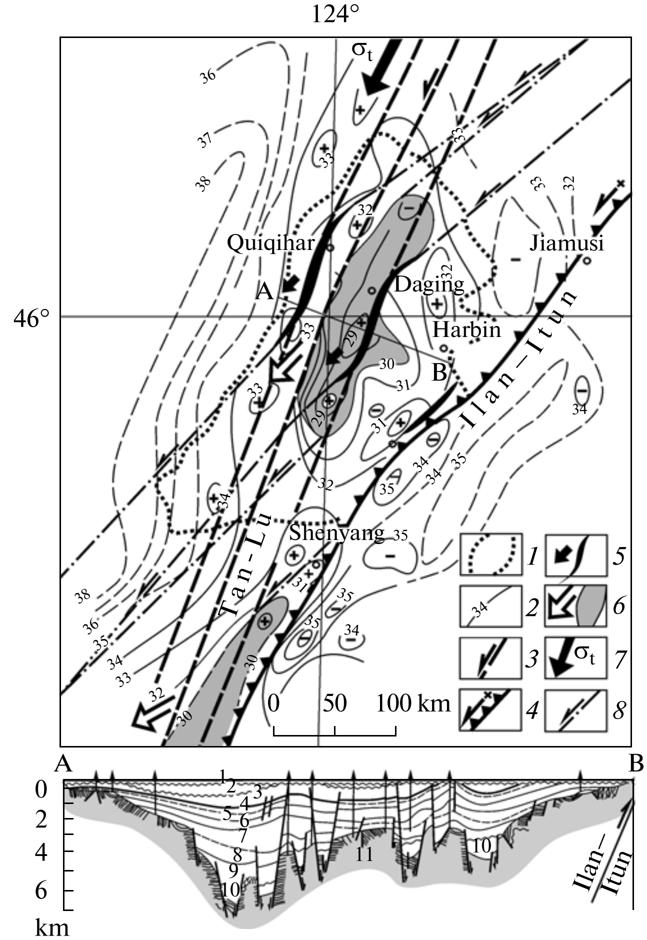

Fig. 4. The schematic structural–kinematic settings for the formation of the Sunlyao sedimentary basin (compiled using materials [68] from [15]).

(*1*) Boundary of the basin; (*2*) isopachs of the Moho surface (km); (*3*) continuation of the Tan-Lu system of strike-slip faults in the basement of the basin; (*4*) position of the Ilan–Itun left-lateral updip-strike-slip fault at the base of the continental crust; (*5–8*) dynamic–kinematic setting responsible for the extension of the Tan-Lu strike-slip fault with the formation of linear grabens (*5*) and mantle asthenoliths (*6*) (the arrows show the direction of the extension forces); tangential compression (*7*); left-lateral strike-slip faults superposed on the Tan-Lu fault system.

Section A–B. The vertical numbers: (1) Upper Cenozoic sediments, (2–9) Cretaceous sedimentary formations; (2) Mingshui and Sifangtai (K_2, Campanian–Maastrichtian), (3) Nanjiang (K_2, Coniacian, (4) Yaojia (K_2, Turonian), (5) Qingshankou (K_2, Cenomanian), (6) Quantou (K_2, Apian–Albian), (8, 9) Denglouku (K_2, Hauterivian–Barremian), (10) Upper Jurassic rocks; (11) heterogeneous basement of the basin.

ceous the Jurassic–Early Cretaceous sedimentation areas at least two times, which corresponds to the amplitude of the horizontal left-lateral displacement confined to the narrow Tan-Lu fault zone. The similar imbricate structure was forming at that time also on the southern flank of the Tan-Lu strike-slip fault. As is known, compression duplexes, where strike-slip faults are transformed into thrusts, develop along strike-slip faults discretely and with different horizontal displacement amplitudes, which is responsible for the different displacement amplitudes in individual segments of transit faults. It is conceivable that the different displacement amplitudes in the southern and northern segments of the Tan-Lu fault are explained by the same factor.

The Central Sikhote-Alin (CSA) left-lateral strike-slip fault [11, 12] is traceable for over 1000 km (Fig. 2). According to the deep seismic sounding data, this steep fault continues to depths down to 40 km and crosses the Moho interface [1]. As a left-lateral strike-slip fault, this structure began forming at least in the Jurassic (not later), and this process was in progress in the Early Cretaceous to be activated in the Late Cretaceous, which is reflected in the left-lateral displacement of Albian–Cenomanian granitoids for 60–100 km. Left-lateral displacements along this fault with an amplitude of approximately 12 km [29] also occurred in the Late Paleogene; its feathering meridional fault with the amplitude of the left-lateral displacement of 30–40 km was formed in the west mainly in the Late Senonian [35]. The integral amplitude of the left-lateral displacement along the Central Sikhote-Alin strike-slip fault is estimated to be 200 km [11, 12] to 250 km or, probably, higher [49, 76].

The Arsenyev left-lateral strike-slip fault is parallel to the Central Sikhote-Alin one gradually joining the latter in the north via the Alchan updip–strike-slip fault (Fig. 2). According to the deep seismic sounding data [1], the fault dips steeply southeastward crossing the Moho interface at a depth of approximately 40 km and exhibits indications of upward displacements. The amplitudes of the horizontal displacements along this fault are unknown, although an easterly adjoining block largely composed of Jurassic–Lower Cretaceous sedimentary rocks is characterized by the intense development of imbricate and thrust structures with a strike of NE 40°–50°. The oblique orientation of these structures allows them to be considered as parageneses (duplexes) of significant left-lateral displacements along the Arsenyev fault.

The Ussuri left-lateral strike-slip fault [40] (Fig. 2) is most readily traceable in the NNE direction from the Amur Bay to the Alchan updip–strike-slip fault joining the latter at an oblique angle. It is conceivable that the fault continues northward along the Ussuri River valley. The left-lateral displacement along this fault for 50 km is established south of Lake Khanka [51]. Along the left margin of the Amur Bay, shear dislocations involve Cenozoic sedimentary formations. Both the Ussuri and Alchan left-lateral strike-slip faults adjoining via the Alchan updip–strike-slip fault the Central Sikhote-Alin fault represent its branches, which translated left-lateral displacements along the northern segment of the latter.

East of the Central Sikhote-Alin strike-slip fault, the above-mentioned left-lateral strike-slip faults are added to by a system of subparallel strike-slip faults (the Vostochnyi, Mikula, Armu, and others), which form the East Sikhote-Alin shear zone at least 150 km wide [38] (Fig. 2). These strike-slip faults cross like a giant cleavage the continental crust with the left-lateral displacement of the Lower Cretaceous sedimentary complexes and Albian–Cenomanian granitoid massifs for 17–30 km. The strike-slip faults bordered large WNW-extending volcano-tectonic structures (Fig. 2), which opened intermittently as extension duplexes in the Cenomanian–Paleocene serving as magma conduits during the formation of the East Sikhote-Alin volcanic belt. The strike-slip faults also determined the kinematic structuring conditions of the Late Cretaceous–Cenozoic ore deposits, thus confirming their activity at that time [38, 40–42, 46, 50, and others].

Thus, the faults of the Tan-Lu–Sikhote-Alin system represent left-lateral strike-slip faults with displacement amplitudes amounting to hundreds of kilometers, which began developing at least in the Late Jurassic (not later) and, probably, in the Triassic [51]. Intense large-scale left-lateral displacements along the Tan-Lu fault came to an end in the terminal Early Cretaceous. Subsequently, the Tan-Lu fault was largely developing as an extension structure, while displacements along the Sikhote-Alin left-lateral strike-slip faults were in progress until the Cenozoic.

The Bohai–Amur system uniting several diagonal near-continental faults is represented primarily by left-lateral updip–strike-slip faults: the Ilan–Itun (II) (Kur in Russia) and Dunhua–Mishan (Alchan in Russia). Branching off from the Tan-Lu fault in the NE (50°–70°) direction (Fig. 1) and extending from the Bohai Sea to the Amur River, these strike-slip faults join at an acute angle the Central Sikhote-Alin left-lateral strike-slip fault (Fig. 2). The faults of the Bohai–Amur system cross the composite Archean–Proterozoic craton with the left-lateral displacement of its eastern boundary up to 100 km (Fig. 2). In accordance with the structural paragenesis, the left-lateral strike-slip faults of the Bohai–Amur system determined the opening of the conjugate Tan-Lu strike-slip fault (Figs. 1, 3). Consequently, at the second stage (terminal Early Cretaceous–Cenozoic), the development of the Tan-Lu fault as an extension structure reflects the main episode of left-lateral displacements along the Bohai–Amur system (in terms of right-lateral displacements along the faults of the Bohai–Amur system [9, 30, and others], the Tan-Lu opening cannot be explained). The main extension phase occurred in the Paleogene resulting in the formation of the Huabei–Bohaiwan and Subei–Yellow Sea sedimentary basins. This provides grounds for the conclusion that the left-lateral displacements along the Bohai–Amur system experienced significant activation at that time. This conclusion is confirmed by the formation of the Cenozoic pull-apart sedimentary basins along the Ilan–Itun fault. As is shown below, the left-lateral displacement component in these basins played the decisive role.

The oblique orientation of the faults constituting the Bohai–Amur system relative to the Tan-Lu–Sikhote-Alin left-lateral strike-slip fault system (Fig. 1), which is consistent with the position and development of their compression duplexes (syn-shear reversed faults, thrusts, and folds) is their another remarkable feature. The formation time of the Bohai–Amur faults as compression duplexes corresponds to the first stage in the development of the Tan-Lu system (Jurassic–terminal Early Cretaceous) in the regime of a left-lateral strike-slip fault. With the termination of the main left-lateral displacements along the Tan-Lu fault in the terminal Early Cretaceous, the faults of the Bohai–Amur system ceased their dominant functioning as compression structures being transformed into left-lateral strike-slip faults. This kinematic reorganization of the Bohai–Amur system is reflected in the changing of the kinematic characteristics of the Ilan–Itun and Dunhua–Mishan faults.

The Dunhua–Mishan fault was developing until the Aptian as an updip–thrust structure and then was transformed into a left-lateral strike-slip fault [8]. The similar almost coeval (mid-Albian) kinematic reorganization is observable in the development of the Ilan–Itun fault. Extending along the southeastern slope of the Sunlyao sedimentary basin (Figs. 1, 2), this fault is distinguishable at the base of the crust. It crosses the Moho interface displacing the latter upward by 4–5 km (Fig. 4). Such a behavior reflects likely the kinematics of a reverse fault characteristic primarily of the first development stage of the Ilan–Itun fault as a compression structure. In the northeast, this fault borders from the northwest the Middle Amur sedimentary basin (Fig. 2). In the geoelectric section, it is expressed as a zone with lowered resistance steeply dipping northwestward and crossing the entire lithosphere [13]. In this area, the development of the fault as a compression structure (reverse fault) was accompanied by the formation of the fold–thrust structure with the distinct SE vergence of the folds and NW dip of the thrust planes. The thorough analysis of the successive Lower Cretaceous turbidite (Amur Complex) structuring revealed its two-stage development. The first stage was marked by the formation of structures orthogonal relative to the NNW compression, which started likely in the Jurassic (or earlier) and lasted until the mid-Albian [24, 25]. At the second and post-Albian stage, the changed kinematic style of the fold–thrust structures in the Amur Complex is reflected in the progressively increasing role of stratal and near-stratal left-lateral displacements. They are accompanied by folds with steep to vertical hinges that complicate limbs of compressed folds with gentle hinges formed at the first deformation stage [25]. The second stage likely reflects the beginning of the transformation of the reverse faulting kinematics in the development of the Ilan–Itun fault into a left-lateral strike-slip one with the corresponding displacement of the eastern craton's boundary for approximately 50 km (Fig. 2).

The imbricate–fold structures of the Amur region are elements of the spacious Sikhote-Alin imbricate-fold system located east of the Archean–Proterozoic craton (Fig. 2). This system was forming during the Jurassic–Early Cretaceous to be culminated in the late Albian in the formation of an imbricate–fold orogen associated with the strike-slip fault. The orogen was subsequently eroded in the Late Cretaceous and overlain by the Upper Cretaceous–Cenozoic cover of the East Sikhote-Alin volcanic belt (Fig. 2). The imbricate–fold structures of the orogen were developing as compression duplexes of the Sikhote-Alin left-lateral strike-slip faults [12, 38, 40, 44–46, 50, 51, and others]. The similarity in the strike (NE 50°–70°) and nature (the parageneses of the left-lateral strike-slip faults), as well as the synchronous (Jurassic–Early Cretaceous) formation of the Bohai–Amur fault structures and the imbricate–fold structures of the Sikhote-Alin strike-slip faults, allow them to be considered as a single system of regional compression structures: the parageneses of the Tan-Lu–Sikhote-Alin system of left-lateral strike-slip faults. The transformation of the faults constituting the Bohai–Amur system as compression structures into left-lateral strike-slip faults stimulated the development of the associated extension structures that controlled the formation of the sedimentary basins during the Late Cretaceous–Cenozoic.

STRUCTURAL–KINEMATIC CHARACTERISTICS AND DEVELOPMENT OF STRIKE-SLIP FAULT CONTROLLED SEDIMENTARY BASINS

Depending on the orientation of the regional strike-slip faults and their morphological–kinematic patterns, the sedimentary basins controlled by them may be subdivided into four types associated with the following: (1) the Tan-Lu strike-slip fault; (2) the Bohai–Amur system of strike-slip faults; (3) the junction areas between the Tan-Lu and Bohai–Amur systems of strike-slip faults; (4) the East Sikhote-Alin system of left-lateral strike-slip faults.

The sedimentary basins associated with the Tan-Lu deep-seated strike-slip fault are represented by the Subei–Yellow Sea (SU), Sunlyao (S), Huabei–Bohaiwan (HB), and Amur–Zeya (AZ) basins, which form a rift zone approximately 3000 km long (Fig. 1). The southern segment of this rift was formed on the thinned (by 10–15 km) continental crust and is characterized by a high thermal gradient. The extension in the southern segment of the Tan-Lu fault commenced in the terminal Early Cretaceous and continued episodically until the end of the Cenozoic. This process

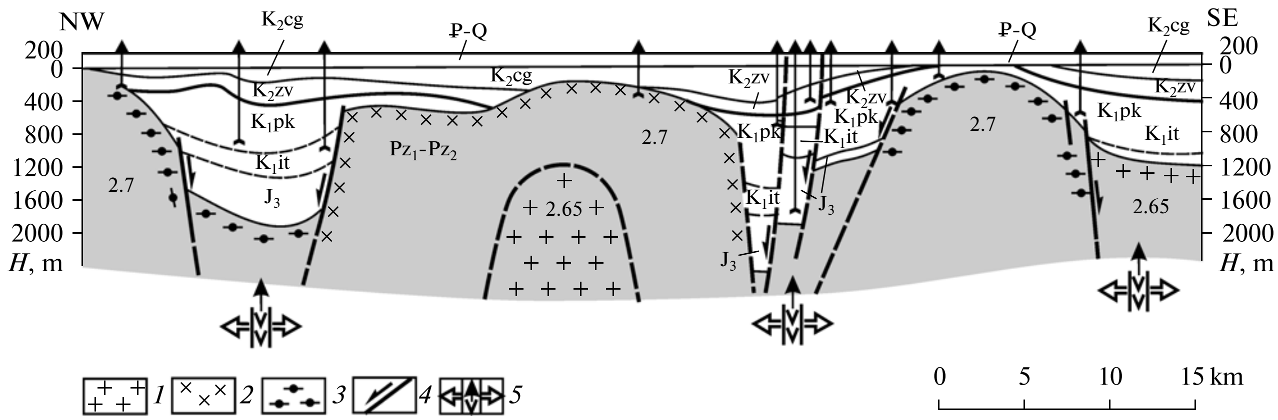

Fig. 5. Schematic cross section of the Amur–Zeya basin (after [2, 54]).

(*1–3*) The basin's basement: granites (*1*), diorites (*2*), gneisses (*3*) (the numbers designate the rock's density); (*4*) normal faults; (*5*) assumed position of the deep-seated faults of the Tan-Lu system, the extension of which determined the subsidence along the normal faults and the magma's migration to the oceanic basin.

The stratigraphic section of the basin's infill: J_3 Ekaterinoslavka Formation (Upper Jurassic), (K_2it) Itikut Formation (Berriasian–Valanginian), (K_1pk) Poyarkovo Formation (Hauterivian–lower Albian), (K_2zv) Zavitinsk Formation (Turonian–Campanian), (K_2cg) Tsagoyan Formation (Maastrichtian–Danian), (₽–Q) Zeya Formation (Paleogene–Quaternary).

resulted in the formation of the rift, which was filled by molasse and red rock formations with subordinate basic volcanics. The Pleistocene basanites with inclusions point to the magma conduit role of the fault, which reached depths of 70–90 km [75]. The Suabei–Yellow Sea and Huabei–Bohaiwan sedimentary basins adjoining the rift valley (Fig. 3) should be considered as opposite flanks of a spacious riftogenic extension structure, whose symmetrical patterns are determined by the opposite stepped normal faults steeply dipping toward its axial zone (Fig. 3, sections). The linear grabens of the Sunlyao and Amur–Zeya sedimentary basins (Figs. 4, 5) formed along the northern segment of the Tan-Lu fault are also symmetrical. The deepest grabens were formed above deep-seated faults of the Tan-Lu strike-slip fault zone involved into extension. The S-shaped configuration of the garbens (Figs. 3, 4) points undoubtedly to the uniform extension mechanism along the entire Tan-Lu fault related to the left-lateral displacements along the diagonal faults. At the same time, the extensions were not strictly synchronous, which is reflected in the relatively distinct differences between the main development stages of the stratified basin sediments. For example, the extension in the Subei–Yellow Sea and Huabei–Bohaiwan sedimentary basins was in progress largely in the Paleogene (Fig. 3, sections). The main extension episode in the development of the Sunlyao sedimentary basin corresponded to the Cretaceous Period (Fig. 4), when over 7000 m of sediments [15] were deposited with the maximal basin's subsidence during the Aptian–Coniacian [68]. The Amur–Zeya basin was largely forming during the Late Jurassic–Early Cretaceous (Fig. 5).

Thus, the extension in the Tan-Lu fault zone was discrete with its migration from the northeast to southwest, which may be explained by the successive activation of the system of diagonal left-lateral strike-slip faults in the NW–SE direction. The Okhotsk–Khingan system of left-lateral strike-slip faults (Fig. 1), which determined the formation of the synonymous volcanic belt, was the first one to be activated. The mechanism of the strike-slip associated extension of the magma conduits was likely similar to that established for the East Sikhote-Alin belt [40, 42, 50, 53, and others]. This extension involved simultaneously the northeastern segment of the Tan-Lu fault with the formation of the Amur–Zeya basin, the sedimentary cover of which includes abundant coeval lava flows [15]. By the end of the Early Cretaceous, the activation of the strike-slip faults migrated southeastward being accompanied by the formation of the Sunlyao sedimentary basin mostly at the Early–Late Cretaceous transition (Aptian–Coniacian). The Late Cretaceous and, mostly, Cenozoic were marked by the activation of the left-lateral strike-slip faults of the Bohai–Amur system, which determined the extension in the southern segment of the Tan-Lu fault. The successive activation of the diagonal left-lateral strike-slip faults in the southeastern direction was likely complicated by the multiple superpositions of new activation episodes (not necessarily with a strike-slip component). This scenario explains the absence of distinct stages in the formation of the sedimentary basins along the entire Tan-Lu fault, except for their asynchronous development as pull-apart structures. Noteworthy is the distinct asymmetry in the development of the Sunlyao and Amur–Zeya sedimentary basins with the erosion of their southeastern slopes (Figs. 4, 5). Such an asymmetry explains the presence of reverse fault components, which determined the syn- and postsedimentation rise of their slopes adjoining the updip–

strike-slip faults in the left-lateral displacements along the faults bordering the basins in the southeast (Fig. 4).

The sedimentary basins associated with the Bohai–Amur system of strike-slip faults are primarily controlled by the Ilan–Itun left-lateral strike-slip fault. In China, relatively narrow, although extended Cenozoic sedimentary basins are distributed along the fault practically continuously (Fig. 6, inset). Their dynamic–kinematic mechanism is interpreted in different manners including the pull-apart one [66]. Such a nature is also likely characteristic of the Tanyuan sedimentary basin (Fig. 6) adjoining in the southwest the Middle Amur sedimentary basin (MA). Being elongated rhomb-shaped, the basin was formed in the junction zone of noncoaxial left-lateral strike-slip faults in the transpression regime. Such settings determined the discrete basement extension along the strike-slip fault with the development of the basin's internal structure in the form of local depressions approximately with equal distances between their depocenters (Fig. 6). The regular an echelon distribution of the depressions is direct evidence for the development of the strike-slip fault in the consolidated crust. In these environments, the stress is transferred preserving the regular organization of the extension structures associated with the strike-slip fault under compression.[1] The local depressions are scoop-shaped and inclined in the SE direction toward the parental strike-slip faults transformed in these areas to normal faults that control the position of the associated extension structures of the basement. By analogy with the ore deposits, the extension structures of the basement associated with the strike-slip faults are primarily transverse systems of NW-trending fractures involved into extension. On the one hand, they initiated the formation of local riftogenic depressions with coal accumulation and, on the other, could provide conditions for the migration of deep hydrocarbon fluids. The section along the line AB in Fig. 6 illustrates the principal model of the geodynamic factor, which controls the depression structures, the coal formation environments, the potential influx of deep hydrocarbon fluids, the gas generation and migration.

The local depressions are separated by faults (Fig. 6) transversely oriented relative to the parental fractures that border the basin, which allows them to be attributed to the structures of the transfer type [80]. The structural bridges between the individual depressions well developed in the riftogenic belts are termed accommodation zones, the origin of which is unambiguous. In the region under consideration, these faults up to 5 km wide, being located largely above the basement uplifts separating the depressions, are characterized by complex outlines (Fig. 7) and represent relatively deep valleys filled with lacustrine turbidites grading into deepwater facies. These sediments are up to several hundred meters thick, thus playing a significant role in the hydrocarbon concentration [22, 80]. The morphological–kinematic features of these faults are consistent with extension structures. It is noteworthy that morphologically similar relatively short extension structures are oriented both northwestward transversely to parental faults and in other directions [67] discretely bordering the depocenters of the depressions. According to the proposed model (Fig. 6, section AB), these extension structures could result from rear gravitational synsedimentary sliding of sedimentary complexes from slopes of depressions toward their depocenters, which continued subsiding. Such a scenario is confirmed by the development of injection structures in the depocenters of some sedimentary basins in the Primorye region [33].

The faults bordering the Tanyuan graben are traceable in the northeast along the northwestern slope of the Middle Amur sedimentary basin (Fig. 8) and interpreted as representing the Lobei–Birofeld link of the Ilan-Itun system of strike-slip faults with a significant extension component [5, 22] (Fig. 9). Along the Ilan–Itun and its feathering strike-slip faults, the basins are arranged in an en echelon manner, which points to the basement's extension in the strike-slip fault zone under compression. Similar to the Tanyuan graben, its Preobrazhenskii and Birofeld counterparts were formed in the rhomb-shaped extension duplex of noncoaxial left-lateral strike-slip faults [Fig. 9]. The identity with the internal structure of the Tanyuan graben is notable at the lower structural level in the morphology of the reflector H_{70} established by seismic prospecting [37] (Fig. 10). As the Tanyuan graben, they exhibit morphologically similar equidistant (15–20 km) scoop-shaped local depressions dipping in the southeastern direction toward the parental Ilan–Itun strike-slip fault. In transverse sections, the grabens are asymmetrical (Fig. 9). Their southeastern slopes are steeply outlined by parental strike-slip faults steeply dipping in the northwestern direction and transformed in the basement extension areas into normal faults. On the contrary, the northwestern slopes of these grabens are gentle, which may be explained by the development of a system of SE-dipping normal faults antitethic relative to the parental faults. Away from the depocenters of the depressions (the basement extension structures), the amplitudes of the antithetic faults became gradually lower with the formation of stepped gentle NW-extending slopes of grabens. The grabens are filled with Cenozoic and, probably, Upper Cretaceous (in most subsided areas) volcano–sedimentary formations [5, 22, and others] reflecting the activation of the left-lateral Ilan–Itun strike-slip fault with synchronous extension in the southern segment of the Tan-Lu fault.

[1] The equidistant distribution of the extension along the strike-slip fault is established in the structures of the ore deposits [45] and is used for predicting the localization of ore bodies. This provides grounds for applying a similar approach for predicting the disposition of individual depressions in pull-apart sedimentary basins associated with strike-slip faults.

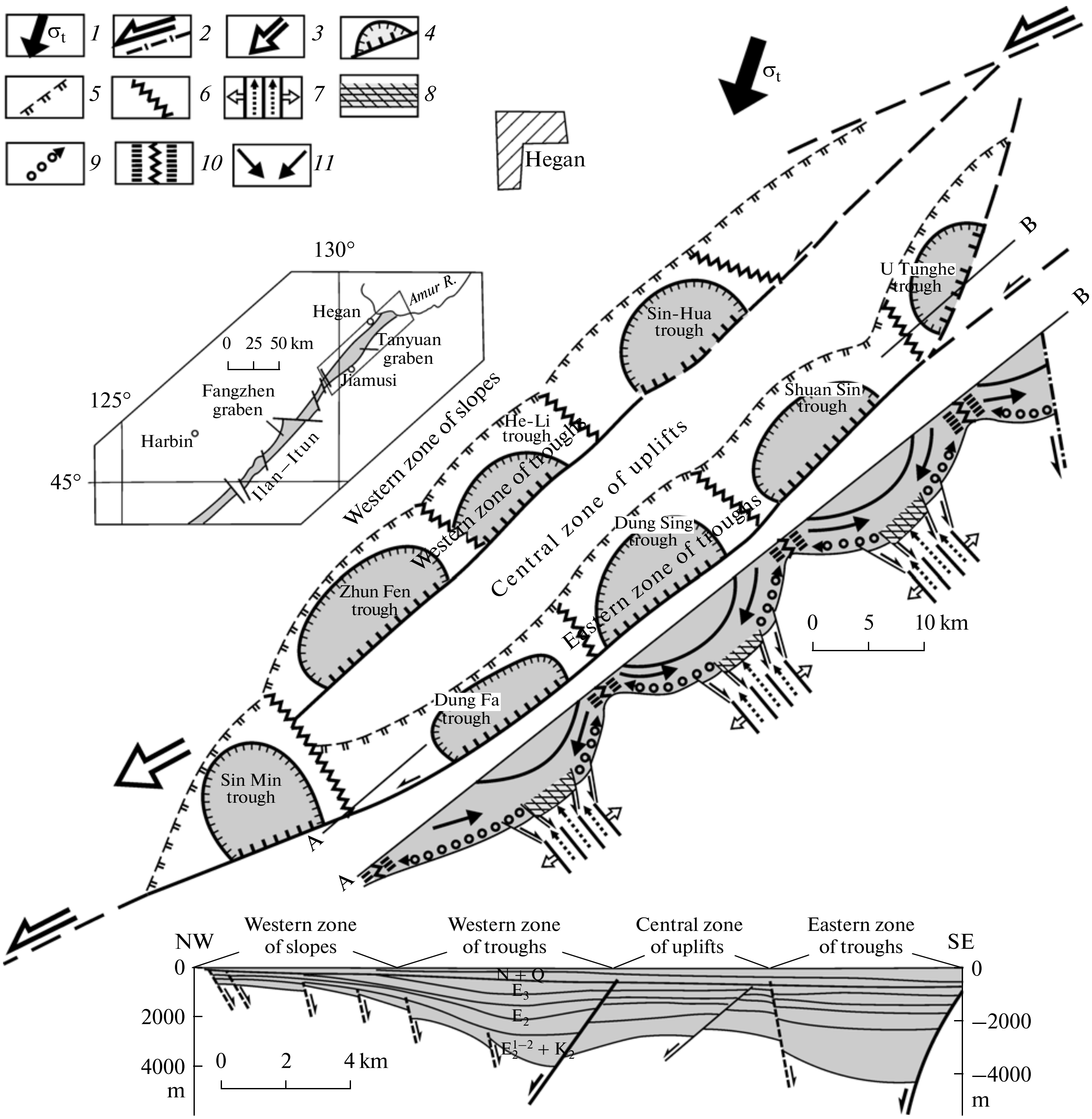

Fig. 6. Schematic dynamic–kinematic formation settings of the Tanyuan graben (compiled using the structural map [67] from [22]).

(*1–3*) Direction of the regional compression (*1*) with the formation of noncoaxial strike-slip faults (*2*) constituting the Ilan–Itun fault and the direction of the extension (*3*) in the conjunction (the Tanyuan graben) duplex of noncoaxial strike-slip faults; (*4*) discrete transformation of strike-slip faults into normal faults in pull-apart areas of the basement with the formation of local troughs; (*5*) generalized northwestern boundaries of the development zones of antithetic normal faults; (*6*) transfer faults (assumed gravitational–sliding extension structures formed above basement uplifts, which separate local troughs).

NW–SE section: transverse structure of the graben after [67] from [22]. The solid lines designate strike-slip faults transformed into normal faults; the dashed lines are antithetic normal faults.

A–B section: principal model of the structural–dynamic settings favorable for the formation of depressions, coal accumulation, gas generation, and the migration of deep hydrocarbons. (*7*) zones of pull-apart extensions in the basement with the formation of normal faults and deep fluid influx; (*8–10*) depocenters of basins with conditions most favorable for coal accumulation and gas generation (*8*) and their subsequent migration (*9*) toward gravitational–sliding synsedimentary extension structures (*10*); (*11*) directions of sliding of the sedimentary complexes to depocenters of troughs with the formation of synsedimentary rear extension structures and frontal injection structures in the depocenters of basins.

In the Sunlyao sedimentary basin, the universally distributed faults of the Bohai–Amur system are best developed along its slopes (Fig. 8). The faults in the southeastern slope of this basin feather the Central Sikhote-Alin left-lateral strike-slip fault. The best studied Pereyaslavka graben formed along the synonymous strike-slip fault consists of local troughs with uniform distances (15–20 km) between their depocenters (Fig. 11) exhibiting complete similarity with the internal structure of the grabens controlled by the Ilan–Itun left-lateral strike-slip fault (Figs. 6, 10). The local depressions are also asymmetrical (Fig. 12). Their southeastern slopes are bordered by synsedimentary steep normal faults, which flattening grade into listric faults and likely inherit the imbricate protostructure of the basement beneath the Sunlyao sedimentary basin [24] formed at the first development stage of the Bohai–Amur fault system (Jurassic–Early Cretaceous) as a compression structure. At the second stage (mainly in the Cenozoic), the transformation of the thrust fault kinematics into the strike-slip ones stimulated the displacements along the steep and gentle fault planes in the development areas of the extension structures associated with strike-slip faults with the formation of local scoop-shaped depressions. Sharing the opinion that the Cenozoic development stage of the Sunlyao sedimentary basin was controlled by the extension determined by the isostatic leveling of the collision zone, which was characterized by the elevated crustal thickness [24, 25], these researchers arrived at a conclusion concerning the undoubted synchronism of the extensions and presumably left-lateral strike-slip displacements.

The faults of the Pereyaslavka group are parallel to the transit Dunhua–Mishan (Alchan) left-lateral strike-slip fault (Figs. 8, 11) pointing to the similarity in their kinematic development. The left-lateral displacements along the strike-slip faults were likely determined by the tangential compression oriented in the SSW direction along the Central Sikhote-Alin strike-slip fault (Figs. 8, 11). The narrow crustal blocks bordered by strike-slip faults experienced during displacements discrete extension (transtension regime) with the formation of local depressions and manifestations of basic volcanism (Fig. 11). Simultaneously, the extension zone that determined the development of the extended East Amur volcanic structure in the Late Cretaceous–Cenozoic (with activation in the Quaternary) was forming along the Central Sikhote-Alin fault behind the southwestward moving crustal blocks (Figs. 2, 11). This was accompanied by the formation of the frontal Nadan'khada imbricate–thrust structure, whose anomalous submeridional orientation is explained by the presence of an indenter in the form of the rigid Jiamusi massif (Fig. 2). The right-lateral displacements along this system of faults determined by the ENE-oriented regional compression (the remote effect of the Indo-Eurasian collision [9 and others]) should result in the formation of compression structures in the zone of their junction with the Central Sikhote-Alin deep-seated fault, which is inconsistent with the above facts.

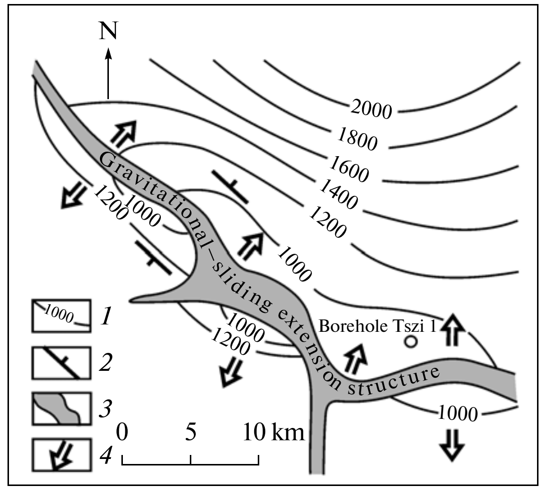

Fig. 7. Schematic morphology and development kinematics of the assumed gravitational–sliding extension structure (compiled using materials from [67] in [22]).

(*1*) Isopachs of the sedimentary cover, m; (*2*) direction of the slope dips in conjugate troughs; (*3*, *4*) morphology of the gravitational–sliding extension structure (*3*) and the kinematics of its formation due to the synsedimentary sliding of sedimentary complexes from the basement uplift toward the depocenters of conjugate basins (*4*).

The sedimentary basins associated with the junction zones between the Tan-Lu–Sikhote-Alin and Bohai–Amur strike-slip faults are morphologically expressed as wedge-shaped structures, which were formed in the junction zones of the Sikhote-Alin left-lateral strike-slip faults with similar fractures of the Bohai–Amur system, primarily with the Alchan left-lateral strike-slip fault (Fig. 2). Crowell [64], who investigated wedge-shaped structures bordered by conjugate strike-slip faults, defined two principally different dynamic settings of their development: under converging strike-slip faults (displacement oriented toward the wedge's apex), the structure experiences compression with uplifting, while, under their divergence (displacement from the wedge's apex), the structure is subjected to extension and subsidence with the manifestation of volcanism and the formation of sedimentary basins. In the region under consideration with diverging strike-slip faults, the extension, which commenced in the terminal Early Cretaceous and discretely continuously continued in the Late Cretaceous and Cenozoic, i.e., synchronously with the development of pull-apart basins along the Ilan-Itun left-lateral strike-slip fault and the formation of the Tan-Lu southern segment in the extension regime, took place behind wedge-shaped crustal blocks moving in the southwestern direction. The compression dislocations (thrusts, folds) observable in some wedge-shaped structures are explained by their development in the general com-

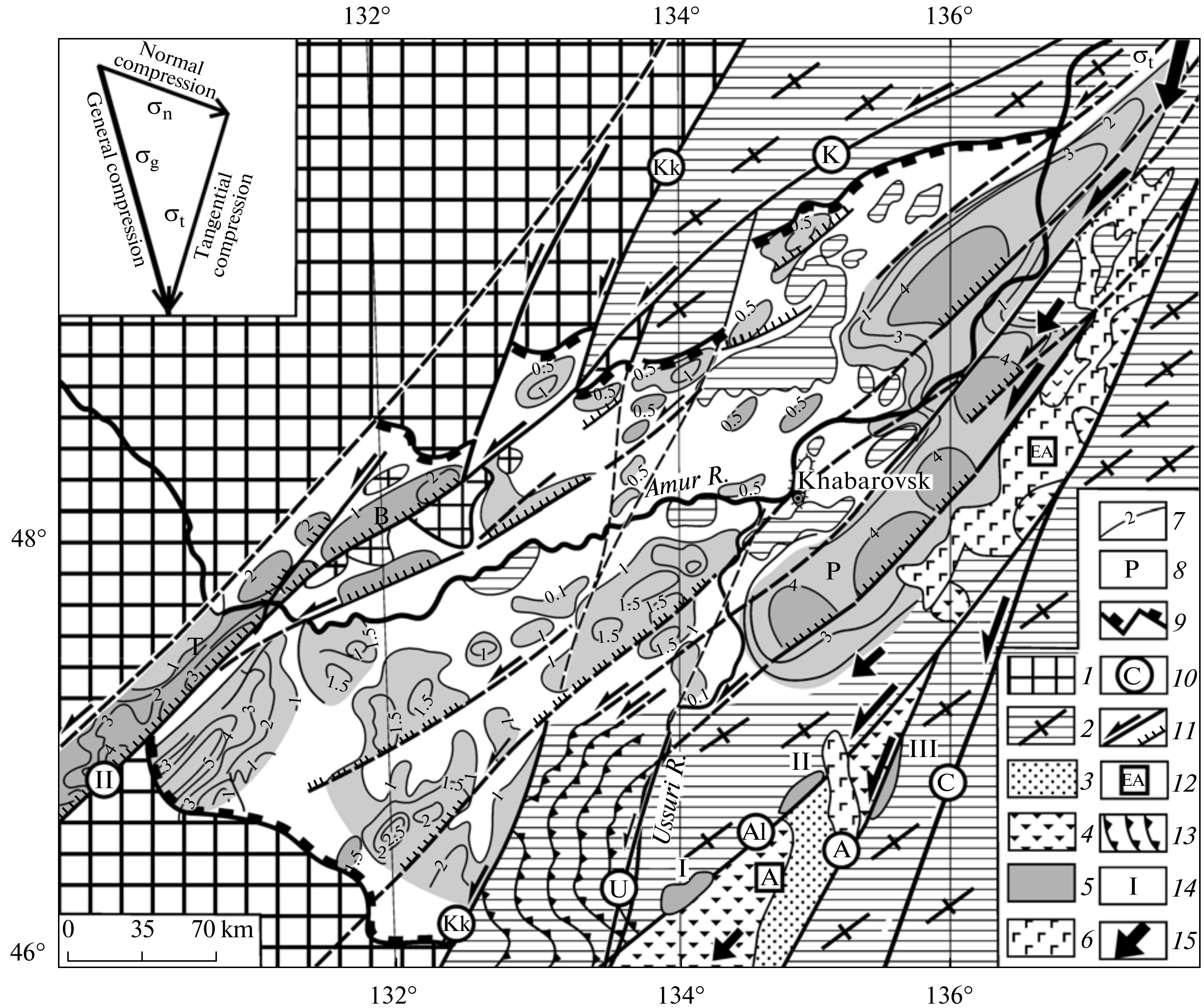

Fig. 8. Schematic structure and dynamic–kinematic formation settings of the Middle Amur sedimentary basin (compiled using materials from [5, 22–25, 28, and others]).

(*1*) Jiamusi–Bureya massif (Precambrian crystalline rocks); (*2*) Sikhote-Alin imbricate–fold system (the structure strikes are shown by dashed lines) composed of Jurassic–Cretaceous mostly terrigenous formations and, less commonly, Paleozoic–Lower Mesozoic siliceous–terrigenous rocks; (*3*, *4*) uppermost Lower–Upper Cretaceous sediments (*3*) and volcano-sedimentary deposits (*4*); (*5*, *6*) Cenozoic sediments (*5*) and Neogene–Quaternary basalts (*6*); (*7*) isopachs of the sedimentary cover (after [16]); (*8*) principal grabens: (T) Tanyuan, (B) Birofeld, (P) Pereyaslavka; (*9*) generalized boundaries of the basin; (*10*) regional faults of the Sikhote-Alin system of strike-slip faults (the thin line designates overlapped basins): (C) Central Sikhote-Alin, (A) Arsenyev, (U) Ussuri, (Kk) Kukan, and Bohai–Amur system of updip–strike-slip faults: (II) Ilan–Itun, (K) Kur, (Al) Alchan; (*11*) Bohai–Amur system of strike-slip faults discretely transformed into normal faults in areas of pull-apart basement extension (the dashed line designates assumed faults); (*12*) wedge-shaped extension structures: (EA) East Amur, (A) Alchan; (*13*) Nadan'khada imbricate–thrust frontal compression structure; (*14*) Cenozoic depressions of the Alchan structure: (I) Nizhnii Bikin, (II) Alchan, (III) Srednii Bikin; (*15*) directions of the pull-apart extension in wedge-shaped structures. The inset illustrates the directions of the general (initiative) compression (σ_g) and its derivatives (σ_n, σ_t).

pression field and also by the probable intermittent transformation of strike-slip faults of the Bohai–Amur system (the post-Albian development regime) into compression duplexes of the Tan-Lu–Sikhote-Alin system of left-lateral strike-slip faults (the pre-Albian development regime).

As is shown in [8], the Alchan wedge-shaped basin was formed in the Aptian–Cenomanian in the dynamic settings of the diverging Alchan and Arsenyev left-lateral strike-slip faults (Figs. 2, 8). At the same time, the concept of the transformation of the left-lateral strike-slip faults into their right-lateral counterparts in the Cenozoic with the formation of the Nizhnii Bikin coaliferous basin [9] is hardly reasonable since, in such a situation, the Alchan and Arsenyev strike-slip faults under ENE-oriented compression [9] should be developing as compression structures. This would require a cardinal change in the basin develop-

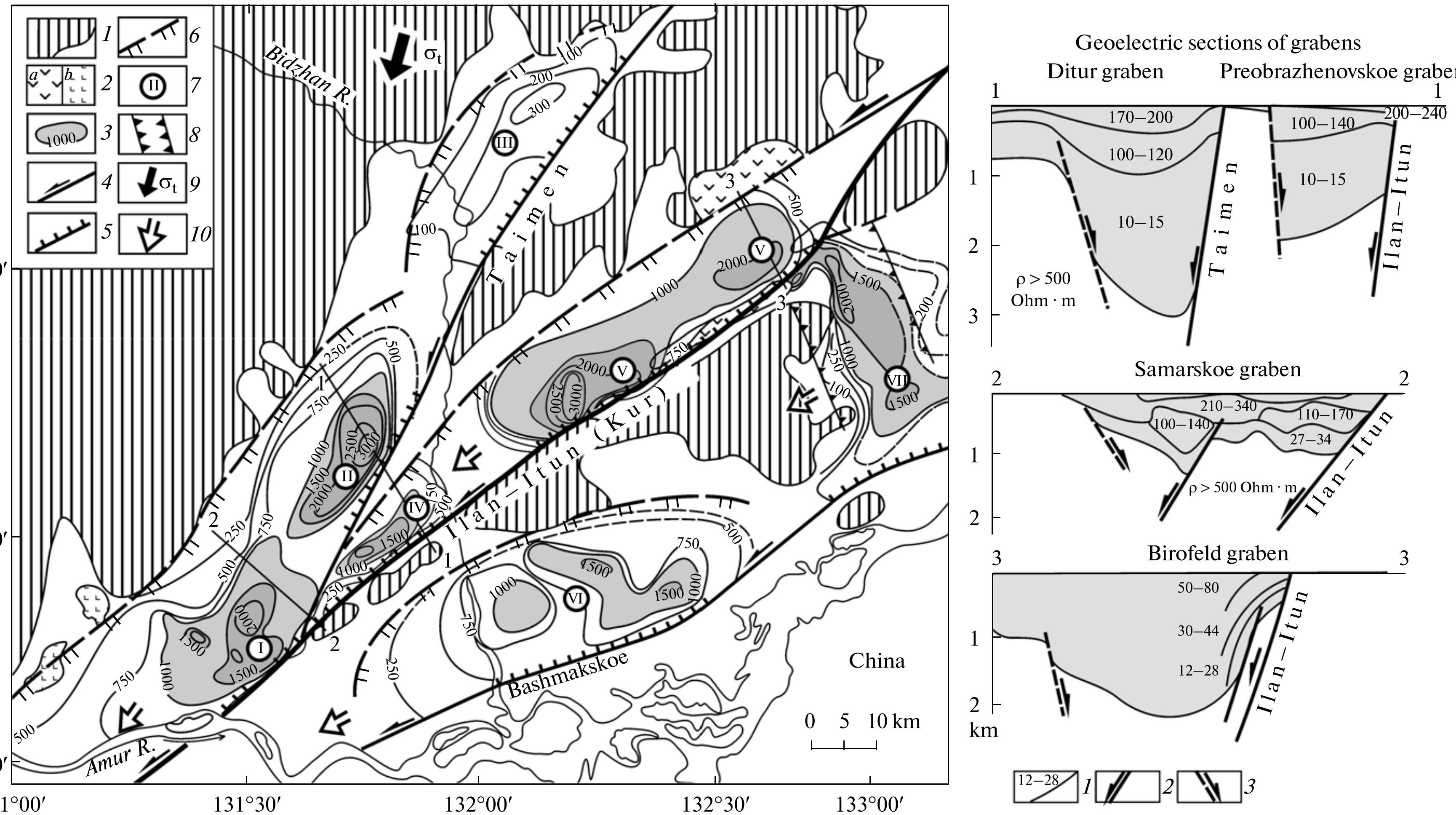

Fig. 9. Schematic structural–kinematic model of the formation of the depressions in the western part of the Middle Amur sedimentary basin (compiled using schematic geological–structural maps from [5, 22, 23, 25, and others]).

(*1*) Basement outcrops (pre-Cretaceous complexes); (*2*) Late Cretaceous (?)–Eocene volcanic rock complex (*a*) and Pliocene–Early Quaternary basalts (*b*); (*3*) isopachs of the Upper Cretaceous (?)–Cenozoic sedimentary infill of grabens and their local deepest (>1000 m) troughs; (*4*, *5*) parental strike-slip faults (*4*) transformed into normal faults in the areas of basement extension zones associated with strike-slip faults (*5*); (*6*) generalized northwestern boundary of the development zones of antithetic normal faults; (*7*) grabens: (I) Lobei–Samarskoe, (II) Ditur, (III) Taimen; (IV) Preobrazhenovskoe, (V) Birofeld, (VI) Bashmakskoe, (VII) Mirolovets; (*8*) transit extension basement structure crossing the crustal block bordered by strike-slip faults; (*9*) direction of the regional tangential compression; (*10*) direction of the basement extension along strike-slip faults.

Geoelectric sections of grabens (after [21, 22] with the insignificantly modified interpretation of the fault nature). (*1*) geoelectric horizons and their specific resistance (Ohm · m); (*2*) parental normal–strike-slip faults; (*3*) antithetic normal faults.

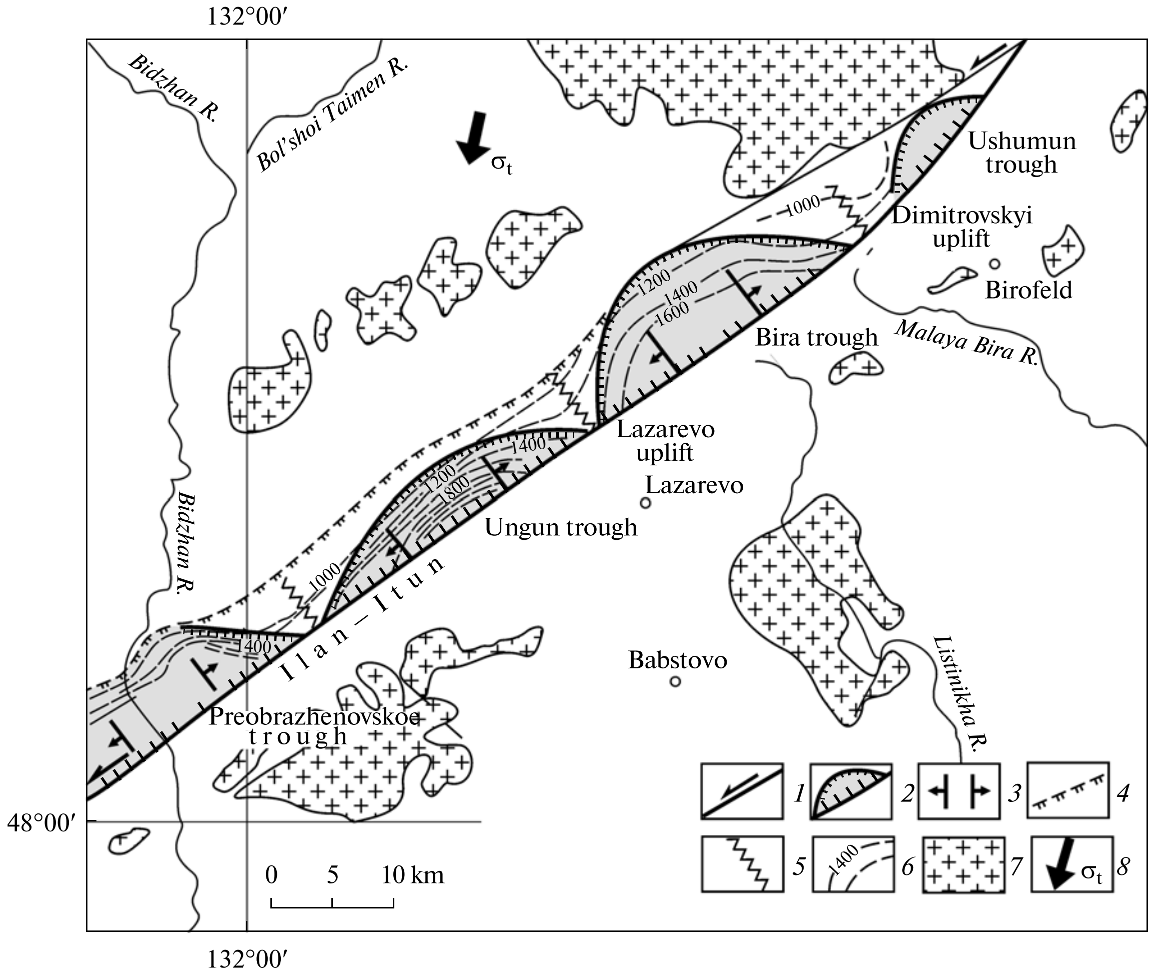

Fig. 10. The internal structure and schematic geodynamic structuring of the lower levels in the Preobrazhenovskoe–Birofeld graben (compiled based on the morphology of the reflector H_{70} established by electric prospecting [37]).
(*1–3*) Parental strike-slip faults (*1*) and segments of strike-slip faults transformed into normal faults with the formation of local troughs (*2*) above pull-apart structures of the basement (*3*); (*4*) generalized northwestern boundary of the development zone of antithetic normal faults; (*5*) axial lines of antiform basement uplifts separating local troughs with the possible development of gravitational-sliding extension structures; (*6*) isolines of the depths (m) of the reflector H_{70}; (*7*) outcrops of basement rocks according to the aeromagnetic survey; (*8*) direction of the tangential compression.

ment dynamics from extension to compression and uplifting, thus providing conditions unfavorable for volcanism and sedimentation. In addition, no particular right-lateral strike-slip faults are established in the region.

The sedimentary basins associated with the Sikhote-Alin system of left-lateral strike-slip faults were formed under local extension in relatively narrow crustal blocks bordered by strike-slip faults [40, 42, 43, 45, and others]. They are the following Cenozoic basins: the Verkhnii Bikin, Zerkal'noe, and others in the eastern Primorye region and the Kraskino, Poima, Narva, Uglovsk, and others in the western and southern Primorye regions. Depending on the width of the crustal blocks, the basins are either symmetrical or, most commonly, extend in the WNW direction, being oriented transversely relative to the strike-slip faults. Some of them contain in their infill a significant share of volcanics, primarily basalts. By their formation mechanism (extension duplexes of strike-slip faults), morphology, and lateral orientation, these basins are similar to volcano-tectonic extension structures widespread in the eastern Primorye region (Fig. 2). It is established that the volcano-tectonic structures multiply opened due to the activation of strike-slip faults serving as magma conduits during the formation of the volcanic cover of the East Sikhote-Alin belt in the Late Cretaceous–Cenozoic [42, 44, 50, 53, and others]. In the Cenozoic, the system of pull-apart structures penetrated through the entire continental crust and reached the mantle, which explains the wide development of basite volcanism in a belt up to 20 km wide

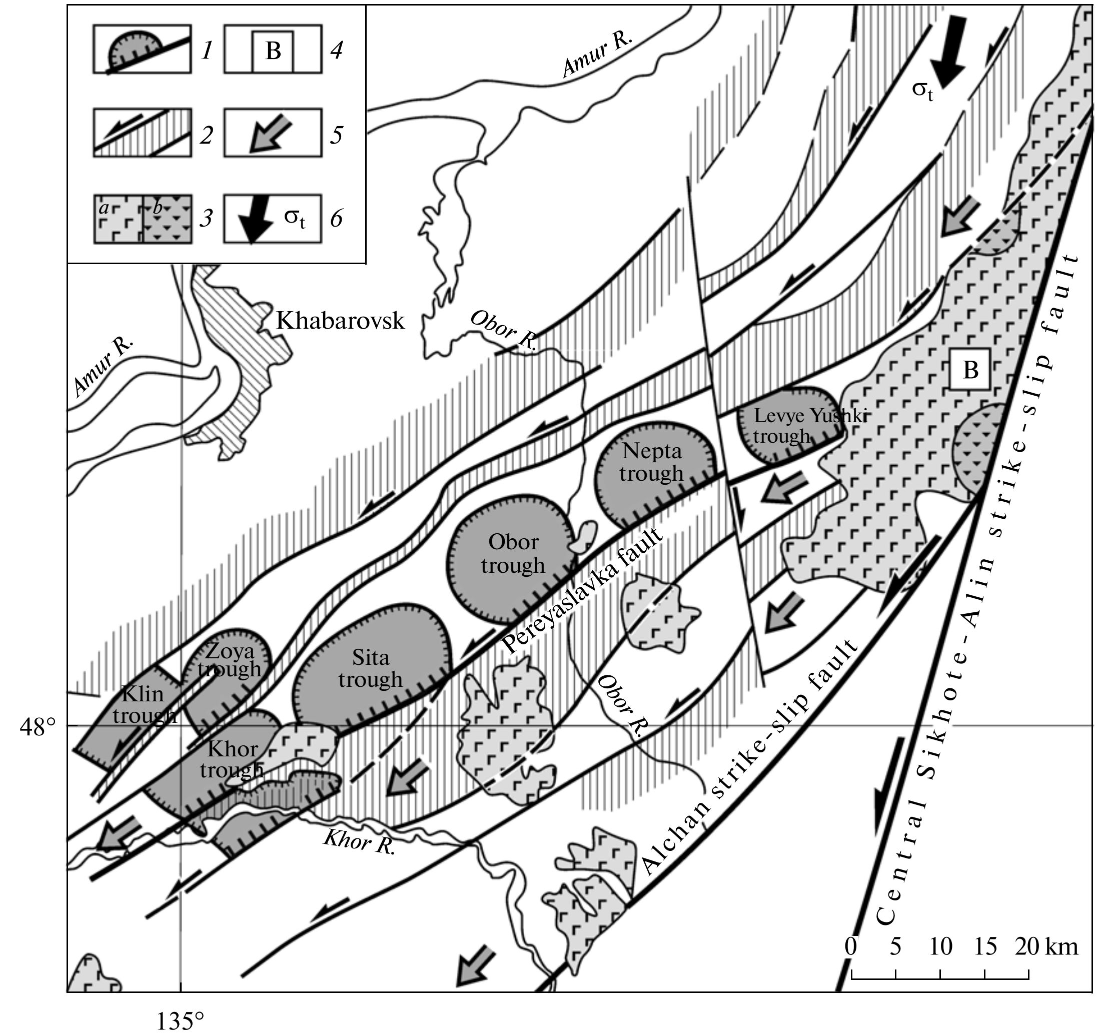

Fig. 11. The schematic structural–kinematic formation model of the Pereyaslavka graben in the southeastern part of the Middle Amur basin (compiled using materials from [23]).

(*1*) Pereyaslavka left-lateral strike-slip fault controlling the formation of the synonymous graben consisting of local depressions; (*2*) uplifts of the folded basement bordered by strike-slip faults (according to the geophysical data from [23]); (*3*) Cenozoic–Quaternary basalts (*a*) and Upper Cretaceous volcano-sedimentary complexes (*b*); (*4*) East Amur volcanic structure formed in the extension zone of the Central Sikhote-Alin strike-slip fault; (*5*) direction of the basement extension; (*6*) tangential compression produced by the left-lateral displacement of the crustal block along the Central Sikhote-Alin deep-seated fault (in response to the general compression).

with the synchronous rise of the mantle (passive rifting). The most significant pull-apart movements of the continental crust took place southeast of the volcanic belt in the Late Cenozoic, which resulted in the further rise of the Moho interface with the formation of the oceanic crust in relatively young basins of the Sea of Japan [40, 44, 45, 53].

The continental crust in the pull-apart structures is variably thinned: from the reduced thickness of 10–15 km in the continental basins to its absence in the deep basins of the marginal seas. These structures demonstrate an important morphological similarity: the crust in them is characterized by the biconvex lens shape, which is termed as an extension neck in the tectonophysics. Such pull-apart patterns of the reduced crust determined, on the one hand, the subsidence along the normal faults with the formation of sedimentary basins and, on the other, the synchronous mantle's rise resulting in passive rifting [40, 53]. This means that the formation of the sedimentary basins and deepwater basins, as well as the synchronous mantle's rise with the injection of mantle asthenoliths, are secondary phenomena determined by the pull-apart processes in the continental crust. The concept of continental rifting under the strike-slip development regime of the eastern Asian margin [40, 42, 44, and others] finds its confirmation in the successive formation of riftogenic structures in response to the crust

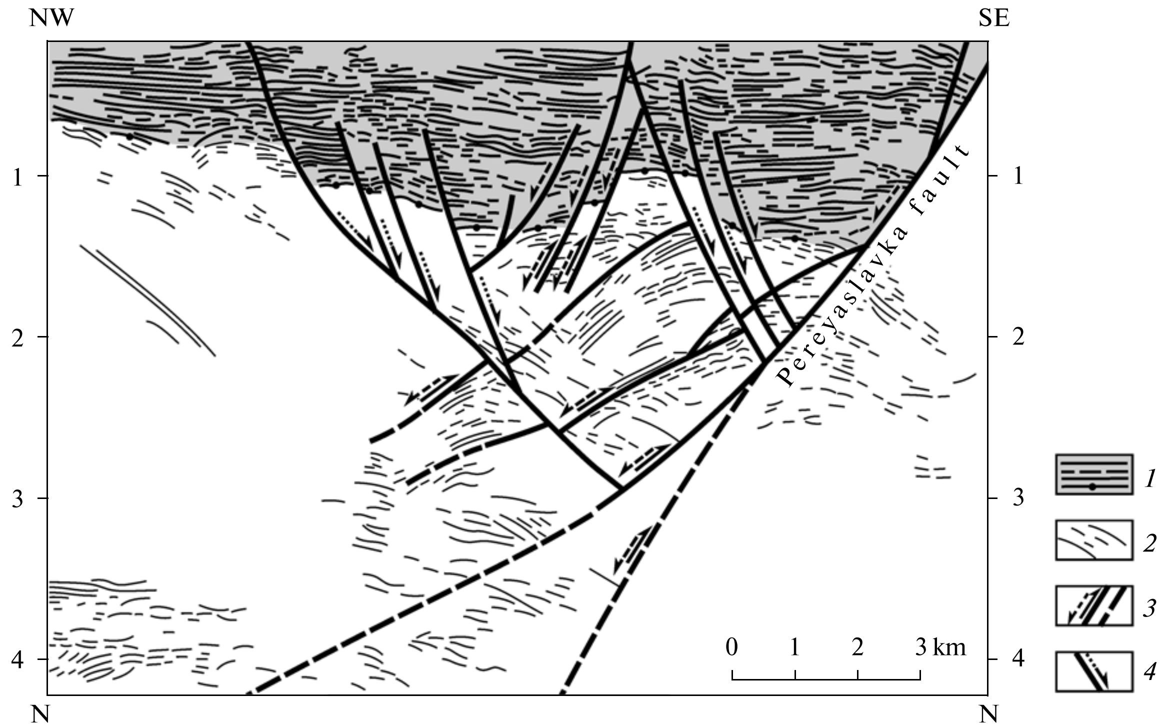

Fig. 12. The structure of the Pereyaslavka graben (Sita trough) (after [25] with the slightly modified interpretation of the probable changes in the fault kinematics).

(*1*) Reflectors in the sedimentary cover (the solid dot designates the base); (*2*) basement reflectors; (*3*) updip–thrusts (the solid arrow) transformed into strike-slip faults or discretely into normal faults (the dashed arrow) in areas of pull-apart basement extension, (*4*) antitethic faults.

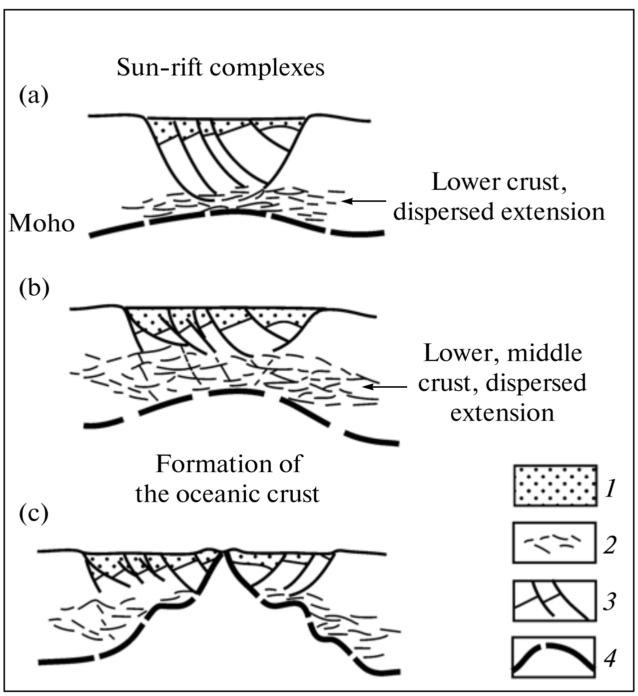

Fig. 13. Schematic principal succession in the development of the rift structures under extension (after [71]).

(*1*) Syn-rift deposits; (*2*) zone of lateral extension in the lower (a) and partly middle (b) crust; (*3*) normal faults (*4*) Moho interface.

extension during the development of the East African rift belt (Fig. 13) [71].

STAGES IN THE DYNAMIC–KINEMATIC DEVELOPMENT OF THE TAN-LU–SIKHOTE-ALIN STRUCTURAL PARAGENESIS (CONCLUSIONS)

Two main stages determined by the changes in the orientation of the dominant stress vectors are definable in the development of the transregional structural paragenesis (Fig. 2, insets). The step-by-step changes in the stress orientation and the responsible factors are known owing to fundamental investigations [60, 63, 70, and others]. According to these researchers, the formation of the strike-slip fault (in response to the primary general compression) is always followed by the transformation of the stress field into a new one, which provides the regular succession of the diverse tectonic structuring. The first and strike-slip–thrust stage (Jurassic–Early Cretaceous) was characterized by the general SSE-oriented compression generated by the pressure of the continental blocks in this direction (Fig. 1). These dynamic conditions stimulated the synchronous formation of the Tan-Lu system of left-lateral strike-slip faults and their structural parageneses (compression duplexes): the Bohai–Amur system of updip–thrusts and the Sikhote-Alin imbricate–fold system (orogen associated with the strike-slip fault). By the Late Cretaceous, the left-lateral displacements along the Tan-Lu fault mostly ceased continuing, however, along the Sikhote-Alin strike-slip fault system, primarily along the Central Sikhote-Alin deep-seated fault. Such structural–kinematic environments provoked the formation of secondary stress fields expressed by tangential (shearing) (σ_t) and normal (σ_n) (relative to the Central Sikhote-Alin strike-slip fault) compressions (Figs. 1, 8; diagrams). A particularly significant role in the regional structuring belongs to the tangential SW-oriented (205°–210°) compression generated by the left-lateral crust displacement along the Central Sikhote-Alin strike-slip fault. This compression determined the transformation of the kinematic characteristics of the feathering steeply dipping faults of the Bohai–Amur system; i.e., reverse faults were transformed into left-lateral strike-slip faults (second stage) (Fig. 2). Due to the activation of the movements along the left-lateral strike-slip faults of the Ilan–Itun and Dunhua–Mishan systems, the southern segment of the Tan-Lu strike-slip fault developed in the Late Cretaceous–Cenozoic in line with the behavior of the structural parageneses as an extension structure with the formation (mainly, in the Cenozoic) of the Subei–Yellow Sea and Huabei–Bohaiwan sedimentary basins on its opposite flanks. Simultaneously, the pull-apart basins, where the left-lateral strike-slip extension component played a decisive role, were being formed along the faults of the Bohai–Amur system. The equidistant distribution of the depressions along the strike-slip faults points to the development of strike-slip faults in the consolidated crust (the basement of the sedimentary basins) in the transtension regime (shear with extension). The transtension was provided by the normal (relative to the strike-slip faults) compression in the SE direction (140°–160°), which restrained, in consistence with the tectonophysics, the displacements along the strike-slip faults. Such a regime was responsible for the dynamic–kinematic settings, which stimulated the development of local extension structures associated with the strike-slip faults, which initiated the subsidence along the normal faults and the formation of sedimentary basins. Simultaneously, synsedimentary compression structures could form in the sedimentary complexes filling the basins against the background of the subsidence along the normal faults. In addition, it should be kept in mind that permanent general near-meridional compression could intermittently activate the pre-Albian updip–thrust development regime of the Bohai fault system. The alternation of the dynamic–kinematic regimes explains the inversion in the development of the sedimentary basins (reversible replacement of extension forces by compression). This is reflected in many the stratigraphic unconformities, the changes in the size of the depositional areas, the replacement of the sedimentary mostly boggy–lacustrine formations by marine facies, and the development of compression structures against the background of the extension tectonics.

Against the background of the changeable dynamic–kinematic settings, noteworthy is the domain of left-lateral displacements along the Bohai–Amur fault system and the Central Sikhote-Alin strike-slip fault in the Late Cretaceous–Cenozoic, which is reflected in the integrity of the paragenetic events: (1) the regular left-lateral displacement of the eastern boundary of the craton by the faults of the Bohai–Amur system; (2) the formation of the Tan-Lu faults at the second stage in the extension regime in response to the activation of the left-lateral displacements along the Bohai–Amur faults; (3) the development of the fault-line pill-apart sedimentary basins with the dominant left-lateral strike-slip extension component; (4) the formation of the extended East Amur volcanic extension structure along the Central Sikhote-Alin strike-slip fault determined by the left-lateral movements along the Bohai–Amur system of faults feathering the latter.

The general near-meridional compression strain responsible for the left-lateral strike-slip kinematics of the Tan-Lu–Sikhote-Alin fault system cannot directly initiate the right-lateral movements along the faults of this system. At the same time, the southwestward displacement of the crustal block along the Sikhote-Alin system of left-lateral strike-slip faults determined by this compression could stimulate the activation of right-lateral movements along the Tan-Lu fault (Fig. 1), which borders the mobile block in the west and lost its left-lateral strike-slip activity in the Late Cretaceous–Cenozoic. At the same time, the episodes of Cenozoic right-lateral displacements along the Tan-Lu fault were probably related to the pulses of sublatitudinal compression, which dominated in the Paleozoic and resulted in the formation, for example, of the meridional fold system in the Primorye region [51].

The structural–kinematic ensembles of the region under consideration (Figs. 1, 2) imply the general SSE vector of the pressure produced by the continental (not oceanic) plates that form the eastern margin of Asia. In my opinion, the existing concept, according to which an important role in the tectogenesis of the remote eastern margin of Asia (the region in question included) belongs to the ENE-oriented compression generated by the collision between the Indian and Eurasian plates, is erroneous. It is known that the transfer of directed compression is possible only in very competent integral medium and ruled out in plastic or tectonized formations, where it becomes "dispersed." The continental crust (tectonosphere) between the Indian Plate and the eastern margin of Asia is intensely tectonized by many differently oriented and different-scale fractures, which makes it unable to transfer compression for such significant distances. Compression could have been realized only in the collision zone between the India and Eurasian plates with the formation of the Himalayan orogen. In addition, it should be kept in mind that the Himalayan orogen is an element of the Alpine–Himalayan compression belt formed along the southwestern margin of Eurasia; consequently, its development cannot be considered separately from this global structure. In my opinion, the formation of the global frontal compression structure resulted primarily from the movement of Eurasia in the SSW direction, which is confirmed by the synchronous development of the East Asian global shear zone (a flank structure as a simple left-lateral strike-slip fault) and the rear extension structure (the breakup and subsidence of the Arctic margin of Eurasia) [32, 40, 48, 52, 53]. The continent motion was likely determined by the permanent equator-oriented rotational forces (Etvesh forces), which involve the whole continent, not only its separate parts such, for example, the margins, as took place during the Indian–Eurasian collision and the probable subduction of the oceanic plate under the continent. The submeridional direction of the global rotational compression is confirmed by the similar orientation of the general compression, which determined the formation of the transregional Tan-Lu–Sikhote-Alin structural paragenesis.

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