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Structure and Evolution of Ancient and Modern Tectonic–Sedimentary Systems

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Abstract—The article discusses the ratio of the size and spatial position of ancient and modern areas of geodynamic processes (tectonic-sedimentary systems) and the resulting geological bodies. It has been established that regardless of the rank and geodynamic affiliation of tectonic-sedimentary systems at all levels, from local to supra-regional, the implementation of geological processes proceeds along the path of least energy expenditure. In the modern structure of the Atlantic-Arctic Rift System, this trend is expressed in the development of strike-slips on the principle of maximum straightening of transfer zones between its segments. In the future, it will also determine progradation of the rift system through Eurasian platform region.

Keywords: Earth's crust, Atlantic–Arctic rift system, rifting, geodynamics, sedimentation

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INTRODUCTION

The Earth's crust, which is a combination of consolidated basement and volcano-sedimentary cover, is extremely heterogeneous and variable, not only in the vertical and lateral directions, but also in time. In a broad sense, this is the largest tectonic–sedimentary system (domain) of our planet, which is formed and altered under the influence of various geological and cosmological factors. As geological knowledge has expanded and instrumental possibilities have improved, ideas about crustal elements and approaches to their mapping have repeatedly changed [1–5, 8, 10, 13, 17, 27, 28, 45]. The traditional separation of tectonic and lithological studies has led to considerable uncertainty in the principles of zoning, mapping, and estimating the economic potential of the crust.

We believe that the extents of mapped lithological complexes and their locations within the crustal profile are proportional to the ranks of tectonic–sedimentary systems. The spatial extents of lithological complexes of local systems are limited to the upper crustal level. Large tectonic–sedimentary systems, combining different crustal levels, are an integrated system all parts of which (volcano-sedimentary cover, basement, and crust) interact with each other, exchanging energy, water, and fluids. In addition, the tectonophysical activity of the asthenosphere plays an important role (e.g., during rifting): anomalously hot asthenospheric mantle material that approaches the crust generates uplift. A heat-induced decrease in viscosity leads to flows in the lower crust, and the complex combination of stress and strain in all overlying layers determines the formation of surface landforms, which in turn determines the profile of the erosion–sedimentary equilibrium of the system. As a result of the formation and transformation of tectonic–sedimentary systems, including those due to isostatic leveling, material redistribution and transformation take place, with the accumulation of various solid mineral resources and hydrocarbon pools, which can occur in both the sedimentary cover and basement rocks.

The fundamentals of this approach are stated in [17], which develop the ideas of A.A. Bogdanov, Yu.A. Kosygin, and L.I. Krasnyi [2, 3, 14–16]. From this perspective, we have determined the characteristic types and spatial extents of constituent elements of different sizes within this domain and have proposed their systematics. In elaborating this systematics, we took into account the following: (1) independence of the systematics of tectonic paradigms; (2) the possibility of mapping based on particular criteria and verifiability of the results; (3) applicability to structural elements and material complexes that evolved on any geodynamic type of crust; and (4) possibility of use for comparison modern and ancient tectonic zones.

CLASSIFICATION OF CRUSTAL ELEMENTS

Similarly to biological taxa, tectonic–sedimentary systems are considered subordinate elements (taxa) in the integrated crustal domain (Fig. 1). This scheme is not intended to generalize all modern and ancient tec-

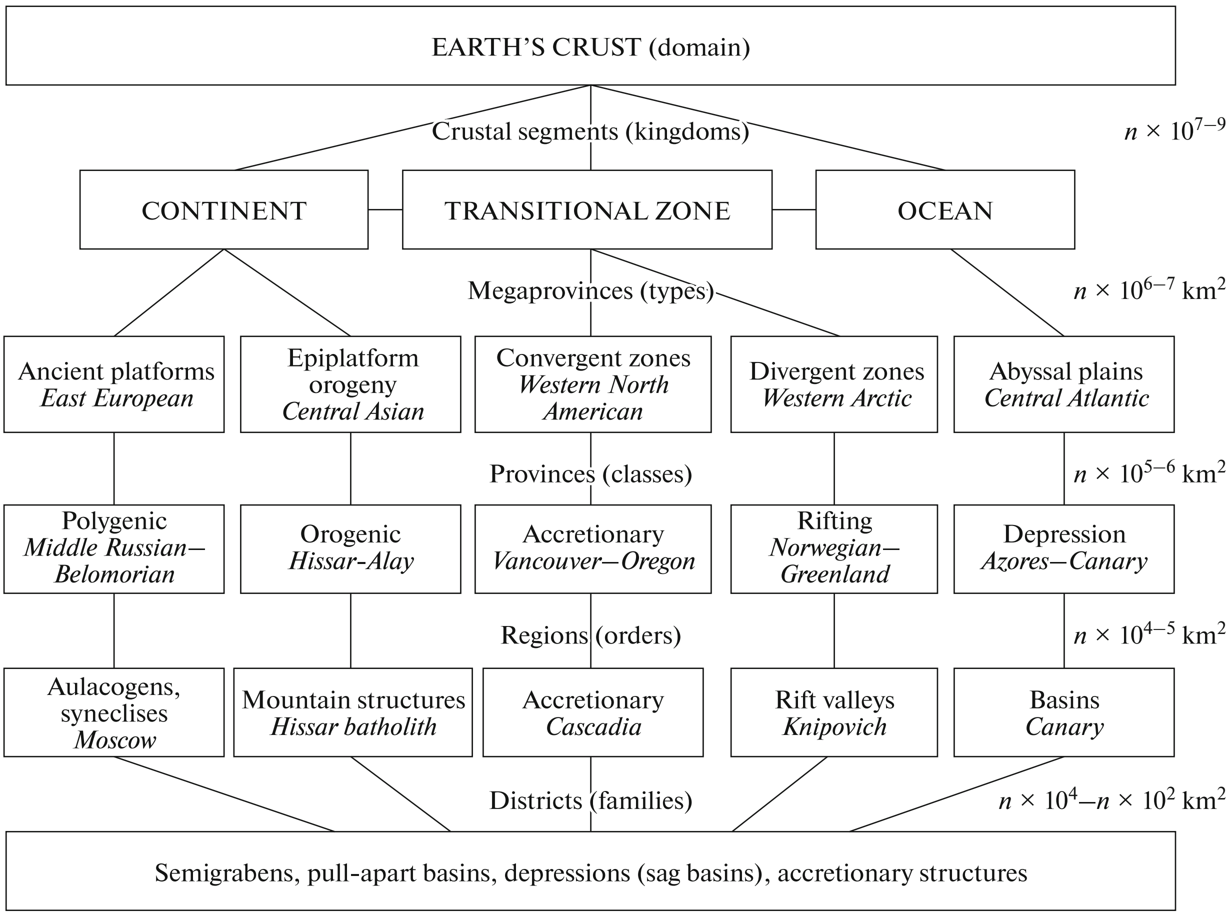

Fig. 1. Scheme of relationships between tectonic–sedimentary systems of different rank.

tonic–sedimentary systems (this is a subject for an independent study); however, it gives an idea of the systematic principles and characterizes certain basic elements of a studied object.

The highest-order taxon of the planetary level (domain), which incorporates all other taxa, is the Earth's crust as a whole, which consists of modern and fossil (including profoundly metamorphosed) volcano-sedimentary units. The Earth's crust is subdivided into segments (kingdoms), which are tectonic zones corresponding to continents, oceans, and transitional zones between them in terms of modern structure and geodynamic regime of their evolution. The areas of segments vary considerably, from $n \times 10^7$ km^2 in the case of mobile belts to $n \times 10^{8-9}$ km^2 for oceans. Remarkably, the spatial extents of segments are inversely proportional to crustal thickness: 70 km beneath orogenic zones, reducing to 0–10 km beneath oceans.

The segments are subdivided into megaprovinces (types). In accordance with geodynamic specialization of segments, there are megaprovinces of platform and orogenic zones, continental margins, and oceanic structures (Fig. 1).

Megaprovinces consist of tectonic–sedimentary provinces (regional-level classes), which are composite structural-morphological zones hosted in the crust of any type. All parts of each individual province have similar geological evolution, and volcano-sedimentary cover unites all stratigraphic complexes accumulated in regional and local landforms at different evolutionary stages. Depending on the aim of studies, finer units can be distinguished within the limits of a province: these are regions (orders) that are determined by spatial distribution and location of stratigraphic complexes, tectonic units, and landforms.

Tectonic–sedimentary provinces consist of a number of families (sedimentary basins). These are lithological units of the local level, characterized by different genesis; their structural features depend on a combination of global, regional, and local factors. The tectonic nature of sedimentary basins can vary considerably both in zones of different geodynamic setting and within the same region during one tectonic stage.

The genetic diversity of sedimentary basins, in the absence of clear criteria for their identification, has led to a considerable difference in the definitions of terms. In addition, the virtual outlining of sedimentary basins in a real geological medium requires the introduction of certain artificial limitations related the capabilities of CDP surveying. For example, this method can be effectively used only in structures with an undeformed or moderately deformed sedimentary cover at least 0.5 km thick in its depocenter [17].

The term *sedimentary basin* does not include all geological objects that form during tectonic–sedimentary interactions, e.g., sedimentary complexes of accretionary wedges developed in crustal accretion zones and the formation of positive landforms. The processes of deformation and lithogenic alterations of the sedimentary cover in the frontal ranges of an accretionary wedge cannot be reflected in any classification using the term *basin*, although accretionary wedges are of economic significance and are reliably mapped tectonic–sedimentary systems with individual evolutionary patterns.

Due to overestimation of the role played by sedimentary basins in the structure of the tectonosphere, they are often taken as universal indicators of geodynamic regimes. In this case, it is usually assumed that the area and volume of crust involved in extensive geodynamic processes considerably exceeds those of an individual basin. Every sedimentary basin, independently of how clearly it is bounded, represents only an element of the more complex "suprabasin" system of processes and structures and it bound by the rules of its evolution.

EXAMPLES OF REGIONAL AND LOCAL TECTONIC–SEDIMENTARY SYSTEMS

Middle Russian–Belomorian Province

The Middle Russian–Belomorian province is located within the megaprovince founded in the pre-Baikalian time and covers the area from Kandalaksha Gulf of the White Sea to areas of the upper reaches of Volga, Dnieper, and West Dvina rivers. Its area considerably changed at different stages in the evolution of the East European Platform. We have drawn the boundaries of this province based on the outline of the Upper Baikalian lithological complex of the Moscow–Mezen subsidence zone (Fig. 2). In terms of the structure of the consolidated crust, orientation of basement structures, and spatial positions of the main Neoproterozoic tectonic–sedimentary systems, we can distinguish three regions within the province: southwestern (Orsha), central (Middle Russian), and northeastern (Belomorian–Pinega).

The present-day structure of the province, which resulted from long-term evolution under different geodynamic settings, is represented by two complexes (stages).

Lower (Preplate or Cataplatform) Structural Complex

The lower structural complex unites tectonic–sedimentary systems, confined between Proterozoic metamorphic rocks of the basement and Upper Vendian sedimentary rocks of the cover. In the reflected-wave field of CDP sections, the lower boundary of this complex corresponds to the B seismic reflector (acoustic basement). The interval above the B reflector is abundant with subhorizontal coherent reflectors traced at regional, zonal, and local levels. The wave field pattern of the underlying interval is chaotic, with irregularly arranged reflectors. The acoustic basement coincides with the boundary dividing rock complexes of contrasting physical properties: (1) stratified deposits of the sedimentary cover and (2) metamorphic rocks of the acoustic basement which yield little information through seismic survey. From the geodynamic point of view, the B seismic reflector, which is traced at the regional level, marks the time when the main orogeny had ceased and the stable stage of crust formation had begun.

The sedimentary basins of the Middle Russian and Belomorian–Pinega regions form complex structural-and-rock assemblages incorporating semigrabens, pull-apart basins, and intermediate structures (Fig. 2). As a result of the sharp asymmetry in the structures of most grabens, the thicknesses of preplate complex deposits vary considerably. For example, they can be up to 5–7 km thick near the steep sides of semigrabens (near the fault planes of normal faults), although they can completely pinch out across the trend of the structure along a distance of 10–15 km. On this background, the Orsha Basin is not alike the others due to the absence of clear tectonic boundaries, making it similar to syneclise-type subsiding basins.

Upper (Plate or Orthoplatform) Structural Complex

The upper structural complex overlies the lower one in a sheetlike manner and considerably exceeds it in distribution area (Fig. 3). The base of the plate complex within the mentioned province is represented mainly by clays of the Redkino Formation, which accumulated in the Late Vendian during the Late Baikalian tectonic stage.

In the reflected-wave field of CDP sections, the lower boundary of this complex corresponds to either the B seismic reflector or R reference reflector, which coincides with the boundary of an angular unconformity between preplate and plate deposits. In the geodynamic sense, preplate and plate deposits characterize the early unstable and late stable geodynamic regimes of the platform evolution, respectively [5, 8]. The main structural forms are subsidence zones with gentle dips. The thickness of this complex ranges from 3–3.5 km in the most subsided Galich and Gryazovets troughs to complete pinch out on the periphery of the

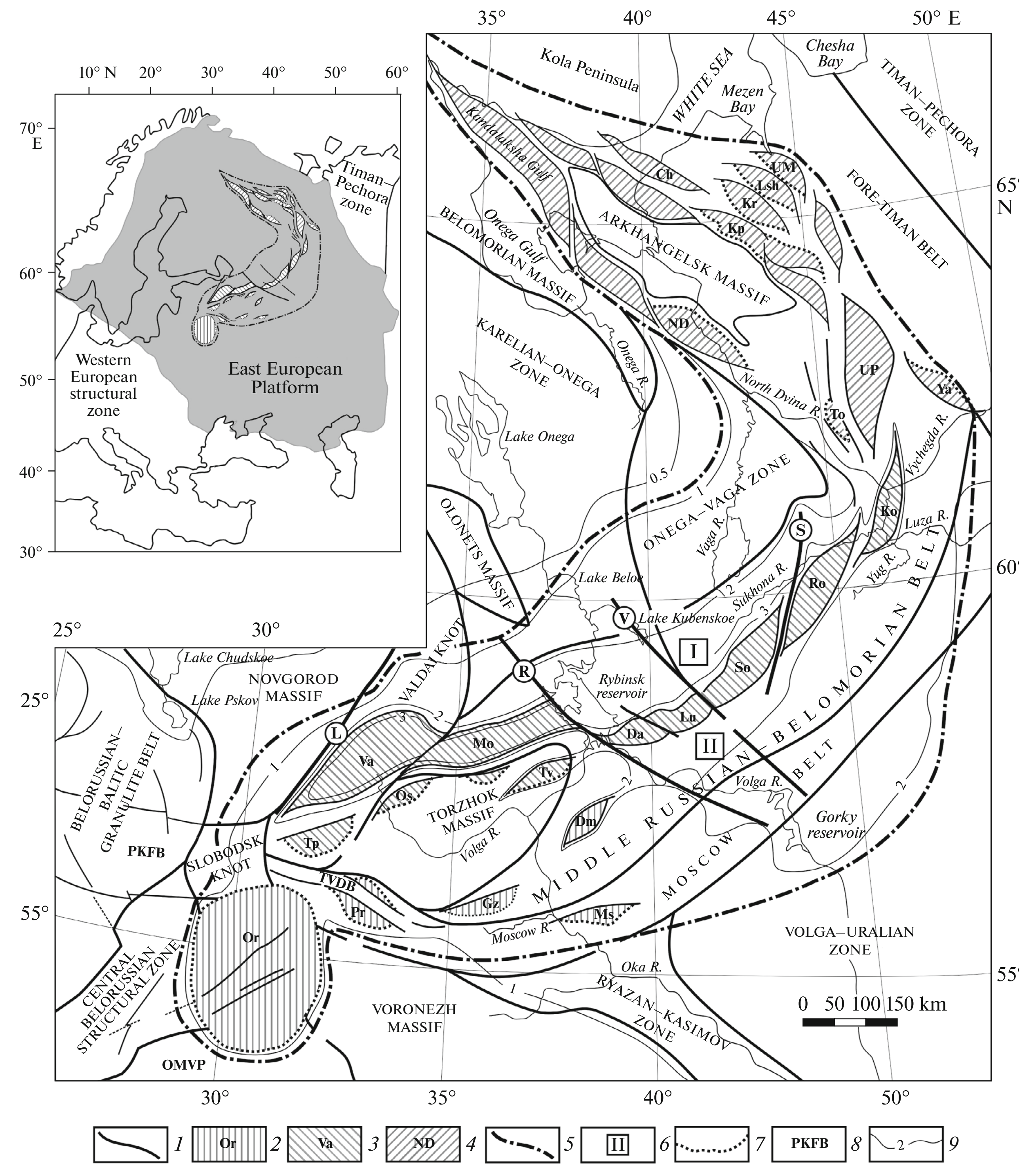

Fig. 2. Tectonic–sedimentary systems of Middle Russian–Belomorian province. Inset shows position of province within East European Platform. Encircled letters denote faults: L, Lovat; R, Rybinsk; V, Vologda; S, Sukhona. (*1*) Boundaries of basement lithological complexes; (*2–4*) preplate sedimentary basins: (*2*) Orsha Basin (Or), (*3*) Middle Russian region (Va, Valdai; Mo, Molokovo; Tp, Toropets; Os, Ostashkov; Tv, Tver; Da, Danilov; Lu, Lyubim; So, Soligalich; Ro, Roslyatino, Ko, Kotlas; Pr, Prechistoe; Gz, Gzhatsk; Ms, Moscow; Dm, Dmitrov–Yaroslavl), (*4*) Belomorian–Pinega region (Ya, Yarensk; UP, Upper Pinega; ND, North Dvina; To, Toima; Ch, Chapoma; Kr, Keret; Kp, Kepino; Lsh, Leshkuonskii; UM, Ust-Mezen); (*5*) boundaries of plate cover distribution (Moscow–Mezen subsidence zone); (*6*) intraplate semigrabens: I, Gryazovets; II, Galich; (*7*) lines of wedging of sedimentary complexes; (*8*) Polotsk–Kurzeme fault belt (PKFB); (*9*) depth of present-day basement surface, km. OMVP and TVDB, Osnitsa–Mikashevichi volcanoplutonic belt and Toropets–Velizh deformation belt, respectively.

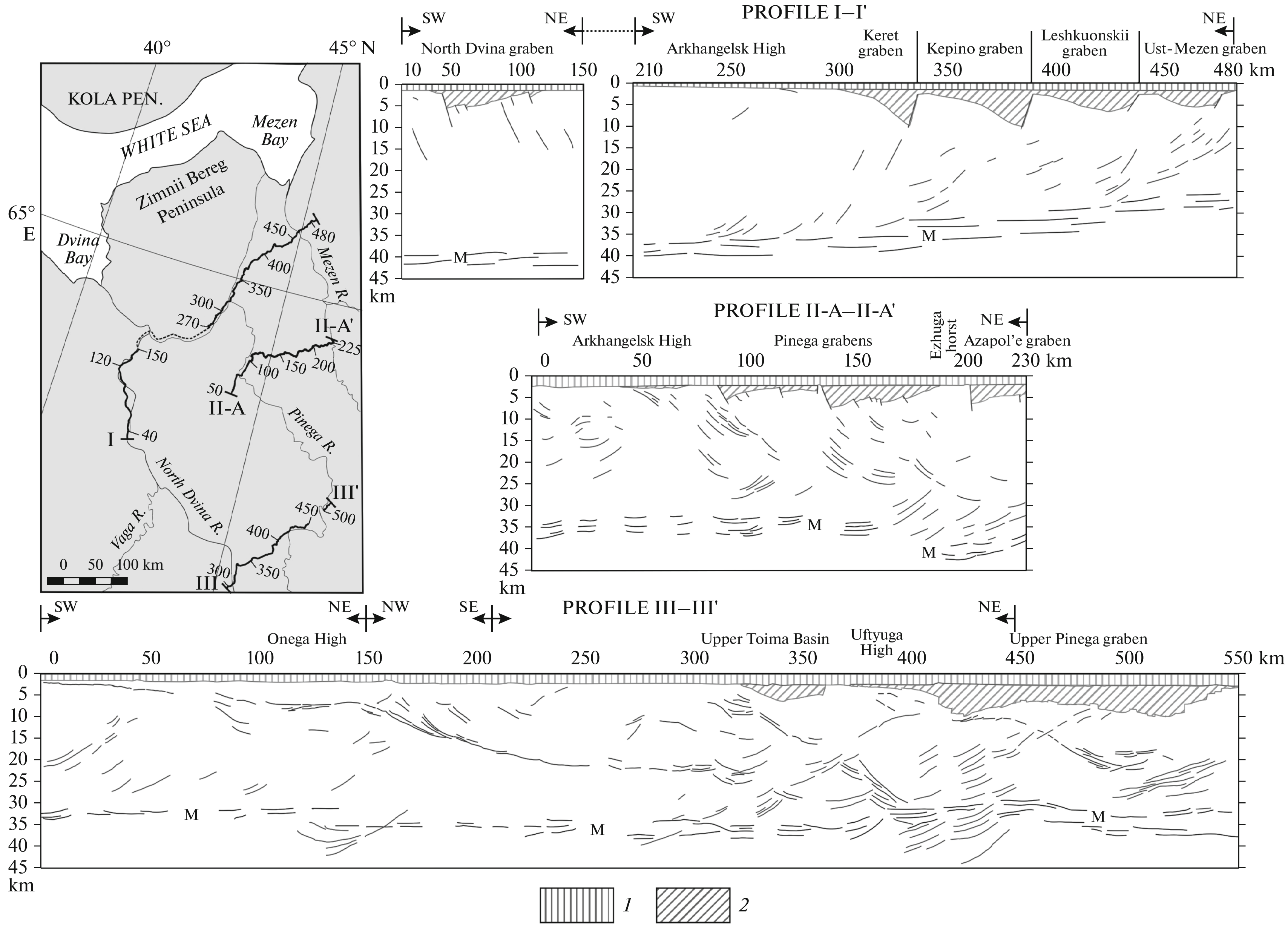

Fig. 3. Seismogeological cross sections of consolidated crust of Belomorian–Pinega region. (*1*, *2*) Sedimentary complexes: (*1*) plate, (*2*) preplate. North Dvina graben is given in projection normal to its trend.

province. An exception is deposits on the northeastern flank, which mostly have tectonic boundaries.

Except for the Orsha Basin, a characteristic feature of the province is its arcuate form in plan view: grabens of the Belomorian–Pinega region are initially almost orthogonal to the orientation of the Middle Russian aulacogen. The greatest change in the directions of trends (about 90°) is observed south of Onega High of the Baltic Shield. To the west, the aulacogen gently bends and aligns with the sublatitudinal orientation of the Polotsk–Kurzeme fault belt [7].

Both in the Middle Russian and Belomorian–Pinega regions, preplate structures in plan view correspond to zones of weak mosaic anomalies. The Middle Russian–Belomorian belt is a crustal zone where rifting structures of both regions coincide (in plan view); it is the least clearly expressed in comparison with the framing basement lithological complexes.

The lower magnetic susceptibility values can be explained by linking formation of the Middle Russian–Belomorian belt and breakup of the collisional orogen. Intracrustal melting which is produced after collision in the thickened crust of orogenic structure (crustal range) leads to migmatization of tectonically coupled heterogeneous units. When disintegration of crustal range, decompression melting leads to formation of granitoid masses. Granites or granodiorites, having about 2.9 g/cm^3 in density and formed at hypabyssal depths, surrounded by rocks of higher densities, would move toward upper crustal levels in accordance with isostatic rules.

This process is favored by intracrustal detachments which often accompany, if not trigger, the breakup of orogens. During the ascent of granitized masses, blastomylonite layers form on detachments. Traces of these processes are commonly manifested in the central and northeastern regions.

Despite the spatial coincidence of province structures and the belt of granitized crust, their formation times are different. The formation of detachments, which is associated with the terminal phases in the breakup of a collisional orogen and removal of metamorphic core complexes has been dated by the closure of the U–Pb system in blastomylonite-hosted titanite at 1750 ± 10 Ma ago [25]. The appearance of preplate tectonic–sedimentary systems within the belt began as late as the Neoproterozoic (Late Riphean).

Seismic survey data supports the presence of a relatively long (during the entire Mesoproterozoic) hiatus sufficient for cooling of crust that had undergone partial postcollision melting. The wave field patterns indicate that structures of the province developed in a cold brittle crust (Fig. 3). Reflectors in seismograms are predominantly gently inclined, which is a characteristic feature of the lower parts of listric faults (detachments). The upper parts of most detachments are marked by boundary normal faults of grabens. The series of inclined reflectors have different vergences, densities, and extents. Some of these series are located only in the middle or lower crust, whereas others run through the entire crust. The observed range of fault vergences reflects cold processes, when the evolution of a detachment system is accompanied by a change in the polarity of stress vector and formation of multidirectional detachments in the brittle consolidated crust.

The crust–mantle interface (referred to as the boundary layer or the M reference horizon) in the Belomorian–Pinega region is reliably identified from reflectors, which sometimes form series up to several kilometers in total thickness. The more complicated structure of the boundary layer, break in continuity, and appearance of steps are observed where this layer is crossed by a series of inclined reflectors ascending to the upper crust. Below the M reference horizon, regular reflectors are mainly not recorded; narrow, linear, steeply inclined zones of concentrated dynamically expressed reflectors can rarely be identified. Beneath the preplate basins of the Middle Russian aulacogen, the consolidated crust is seismically more isotropic and does not contain regional reflectors. The Moho is conditionally outlined from the reflector series within the limits of tabular zones of higher reflectability; its depth is approximately 41–42 km.

Analysis of CDP data has verified the different character of the Orsha Basin compared to structures in other regions of the province in terms of both wave field patterns and belonging to the upper seismic complex acting as the boundary between preplate and plate reflectors [25]. In contrast, the Middle Russian and Belomorian–Pinega regions appeared to be quite comparable to each other in terms of both the preplate structure of the cover and main structural patterns in the consolidated crust. Their general features are (1) the absence of regular (obligatory) thinning of the consolidated crust beneath sedimentary basins and (2) a comparable intensity of extension.

Two these factors indicate the common nature of these regions. Local differences in crustal structure and structural organization of the basins are caused by the spatial relationships between Neoproterozoic faults and the regional structure of the blastomylonite belt, by the composition and degree of reworking of the basement, or a combination thereof. The structural, lithofacies, and seismostratigraphic data indicate there is an unambiguous spatiotemporal relationship between the evolution of extension-related systems in the Middle Russian and Belomorian–Pinega regions. Regional tectonic–sedimentary systems do not fit the structural plan of the basement in detail, but generally fit the combined arcuate Middle Russian–Belomorian belt that frames the Baltic geoblock. Neoproterozoic basins controlling the formation of sedimentary basins are aligned at depth with elongated detachments that reach the M surface. Extension systems are formed by composite troughs with comparable extension rates, indicating the similar energy potential of the entire extension process. Neoproterozoic sedimentary complexes filling the basins demonstrate similar lithofacies, mineralogical-petrographic, and paleoenvironmental characteristics. The results of micropaleontological studies show that the sedimentary complexes in regions are not older than Upper Riphean. The currently available seismostratigraphic data indicate that sedimentary complexes of the platform cover belong to the united structural stage. The basic rule underlying the formation of structures in both systems was the principle of energy cost minimization: crustal faults and associated basins adjusted to the available space in the upper brittle crust and branched to pass by the large tectonic outliers (Arkhangelsk and Torzhok massifs), but when there were no interfering objects, they tended to be aligned along the general axis of the strike-slip. The general discordance between the axes of troughs in the tectonic couple and general southwestern orientation of the areas with high-standing M surface suggests the secondary character of M surface uplift with respect to crustal extension; therefore, it may be the consequence of alignment of stresses that controlled shear motions in the crust. The tectonic–sedimentary systems of both regions formed under the influence of a simple shear mechanism.

The mentioned similarities allow us to consider the Neoproterozoic tectonic–sedimentary systems of the Middle Russian and Belomorian–Pinega regions as geodynamically coupled structural elements of the province, i.e., Middle Russian–Belomorian tectonic couple. The evolution of this tectonic couple took place during the united (but not one-stage) geodynamic process that produced stress fields of similar energy potential but of different orientations in adjacent regions. As a result, either right-lateral or left-lateral strike slips dominated in different parts of the tectonic couple (in the northeast and southwest, respectively).

Middle Russian Region

Analysis of the modern structure of Middle Russian region reflects the sharp asymmetry in the evolution of tectonic–sedimentary systems during its plate stage. The large transverse Rybinsk fault acts as a bisymmetry axis: it not only disrupts the integrity of the aulacogen, but also divides the syneclise into two sharply asymmetric parts (Fig. 2). To the west of the fault, the largest depths of the basement are observed within the relatively narrow band of the Valdai and Molokovo grabens. To the east of the fault, depths of 2–3 km have been revealed at considerable distances (several hundreds of kilometers) from grabens of the aulacogen and mark the large Galich and Gryazovets troughs in the south and north, respectively. Areas where Vendian preplate deposits abruptly thin on the background of thickening Upper Vendian plate deposits can be found only to the east of the fault, along the axis of the aulacogen. This is likely related to the ascending and descending motions of individual parts of the aulacogen, alternating each other in time; however, the exact reasons why particular blocks move and the respective driving mechanisms are unclear. In addition, deformations of the plate cover, which make up the elongated Soligalich (Rybinsk–Bobrovo) megaswell above grabens of the aulacogen, have been revealed only in the eastern part of the syneclise.

Let us consider the evolution of the region as one of a long-lived tectonic–sedimentary system, within which the position of the aulacogen (and the position of syneclise later) were predetermined long before rifting started in the Neoproterozoic. The preceding migmatization, decompression melting, and dynamometamorphism that accompanied the breakup of the collisional range in the Paleoproterozoic resulted in relatively light and permeable crust in the Middle Russian–Belomorian belt, which facilitated the evolution of a regional strike-slip fault. Sedimentary basins of the Middle Russian region formed in the Neoproterozoic, when, simultaneously with the evolution of the regional (main) left-lateral strike-slip fault, en echelon extension fractures formed, as did the structural parts of grabens along the overall growth line of the aulacogen (Fig. 4a). The change in structural plan of the region during the transitional stage of the platform's evolution, between preplate and plate, led to the transfer displacement of an initially linear regional strike-slip fault and the appearance of a rigid Archean massif along its path (Fig. 4b). The occurrence patterns of compression and extension zones with respect to the bend of the regional strike-slip fault have already been considered in some detail, e.g., in [24, 41, 42, 44, 48]. According to these patterns, right-lateral displacement along the Rybinsk transfer fault and appearance of a rigid massif on the path of propagation of the Middle Russian main left-lateral strike-slip led to the formation of the intensive compression zone in the Danilov–Lyubim segment of the aulacogen, with the associated upward ejection of crustal blocks, and to the complete or partial erosion of preplate deposits. Compression of the crust in the bend zone was accompanied by foundation of the Soligalich compensatory basin, which was filled with proluvial-alluvial variegated deposits transported from the ejection zone. Development of grabens in the Valdai–Molokovo segment of the aulacogen at that time ceased due to compensation of the regional strike-slip with the Rybinsk–Vologda (Danilov–Lyubim) compression duplexes.

At the plate stage, the existence of the transfer fault running through the entire crust played a key role in formation of the structural plan of the growing syneclise. The relaxation regime within the platform led to a large normal fault along the Rybinsk transform fault, and that normal fault was abruptly discordant with the axis of the aulacogen (Fig. 4c). Progressive subsidence of the footwall (Gryazovets–Galich semigraben) was complicated by the presence of a chain representing aulacogen segments (lithological inhomogeneity) ori-

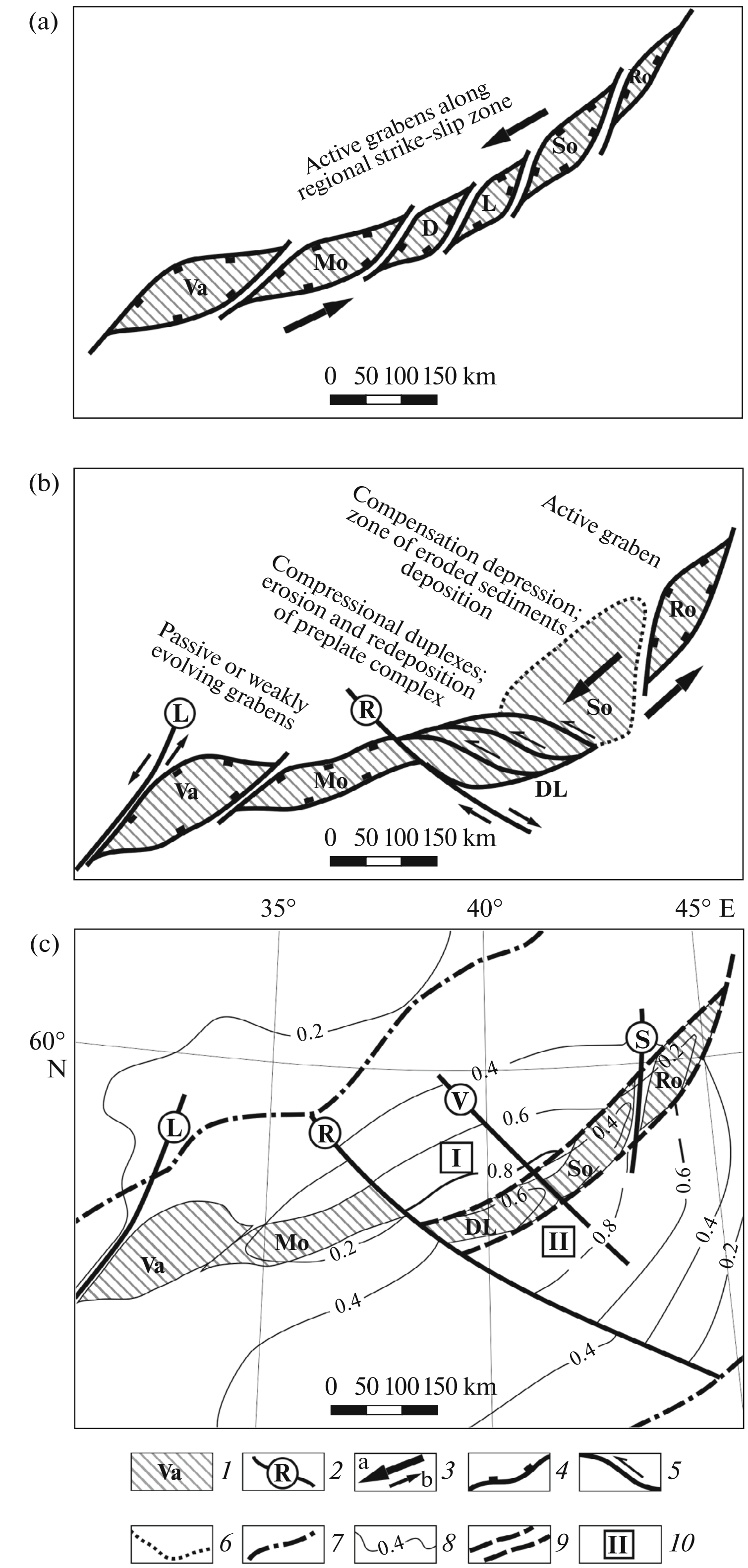

Fig. 4. Scheme of changes in tectonic–sedimentary settings at different evolutionary stages (a–c) of aulacogen and syneclise. (*1*) Sedimentary basins of aulacogen (Va, Valdai; M, Molokovo; DL, Danilov–Lyubim; So, Soligalich; Ro, Roslyatino); (*2*) regional faults (L, Lovat; R, Rybinsk; V, Vologda; S, Sukhona); (*3*) directions of strike-slip faults: (a) regional, (b) transfer; (*4*) oblique normal faults; (*5*) oblique reverse faults; (*6*) zone of compensatory subsidence; (*7*) outline of syneclise; (*8*) stratoisohypsal curves of base of plate complex for Late Vendian; (*9*) activated lateral faults of aulacogen; (*10*) secondary semigrabens: I, Gryazovets; II, Galich.

ented orthogonally to the normal fault. Since these anomalously light crustal fragments of the aulacogen were subsiding at a slower rate compared to the frame, inverted structures appeared and evolved in the plate cover; additionally, the Gryazovets–Galich semigraben was separated into two mutually isolated secondary structures. This mechanism was valid throughout the entire subsidence history of the Moscow syneclise. Every subsidence stage led to disruption of isostatic equilibrium within the domain of anomalously light crust. The subsequent emergence of segments of the aulacogen led to uplift of the Soligalich megaswell.

Areas of the Middle Russian Aulacogen

During the evolution of the main left-lateral strike-slip fault, local inhomogeneities in the basement in the Middle Russian region determined its response to applied regional tectonic stresses and led to the formation of genetically related, but structurally isolated sedimentary basins. Despite the general similarity of processes determined by the regional stress field, each graben was an independent tectonic–sedimentary system, and this is reflected in individual facies and the mineralogic–petrographic composition of sedimentary complex fill.

Variations in local extension conditions caused the formation of two fundamentally different structural-facies types of grabens. The predominant landforms are wide (from tens to hundreds of kilometers) and relatively shallow (no deeper than 3.5 km) grabens in sections of which a regressive sequence of sedimentary facies is observed: from gray deep lacustrine to alluvial–proluvial subaerial sediments (Molokovo type). Another type (Roslyatino) is represented by narrow (up to several tens of kilometers) and deep (5 km, probably, deeper) grabens reported only on the northeastern flank of the aulacogen: their sections are comprised of alternating deep and shallow lacustrine facies (gray and variegated deposits, respectively).

The influence of local tectonic processes which determined the individual character of evolution of every particular graben in the Middle Russian aulacogen is manifested the most clearly in the nonsimultaneous appearance of specific clastic material of different character and intensity in the respective sedimentary sections. On the background of a stable composition of clastogenic matrix of terrigenous deposits of the Molokovo Series (Neoproterozoic), intervals ranging from several tens to several thousands of meters thick have been revealed, where a heavy sandstone fraction was precipitously enriched (35–95%) in acute-angled epidote grains [25].

In general, the distribution of detrital epidote from bottom to top within the anomalous interval can be described as follows: the appearance of significant amounts in heavy fraction, the attaining of maximum values, and a gradual decrease. One epidote-enriched interval appears most frequently in sections; however, there are at least three such intervals in the Roslyatino well (more than 4.5 km deep). The positions of "epidote-rich" intervals in the sedimentary sections of grabens can be subdivided into three types (named after the respective grabens): Molokovo, intervals occur near the basement; Bobrovo, intervals occur quite far from the basement (tens and hundreds of meters from it); and Roslyatino, the interval corresponds to the entire sedimentary section or majority of it.

Certain features (such as the relative instability of epidote in the hypergenesis zone, nonroundness and fresh appearance of fragments, and absence of a relationship between epidote input and the contents of the main rock-forming components) indicate that epidote anomalies formed owing to local sources. Comparison between epidote crystals and grains from blastomylonites and sediments showed that they have similar habits, sizes, and optical characteristics and contain 25–30% pistacite component (this is characteristic of secondary epidote that forms pseudomorphs after biotite and amphibole under partial melting conditions). Analysis of possible mechanisms for the geodynamic evolution of the Middle Russian aulacogen, structure of the grabens it is comprised of, and structure and composition of the upper consolidated crust suggest that the sources of specific clastic material were epidote-enriched blastomylonites that occurred among metamorphic basement rocks as layers with anomalous petrogeophysical properties. Anomalous layers of blastomylonites are considered relicts of rock associations of detachment zones formed at the boundary of tectonic slabs. The isotope age of blastomylonites suggests that these processes took place in the Paleoproterozoic and referred to the tectonic prehistory of the Middle Russian aulacogen foundation. During the long-term period of the Mesoproterozoic, Paleoproterozoic postcollisional processes gradually faded and had completely finished by the time of occurrence of the aulacogen's grabens in the Neoproterozoic; as well, the internal structure of the basement (probably with some later superimposed local deformation) was completely formed by that time.

The distribution patterns of epidote-rich intervals in the sedimentary section can be explained by the relationship between orientation of Neoproterozoic normal faults and Paleoproterozoic blastomylonite layers. Molokovo-type intervals, reflecting epidote input into sediments after formation of the graben with subsequent termination, form with the initially gentle near-surface occurrence of a blastomylonite layer (Fig. 5a). The hanging part of the layer becomes the bottom of the graben, while the other part is removed to the erosion zone as a result of isostatic uplift of the footwall (Fig. 5b). Further evolution of the graben leads to burial of hanging wall, ongoing uplift of the footwall, progressive erosion, and withdrawal of the upper fragment of blastomylonite layer from the zone of influence of the growing graben (Fig. 5c).

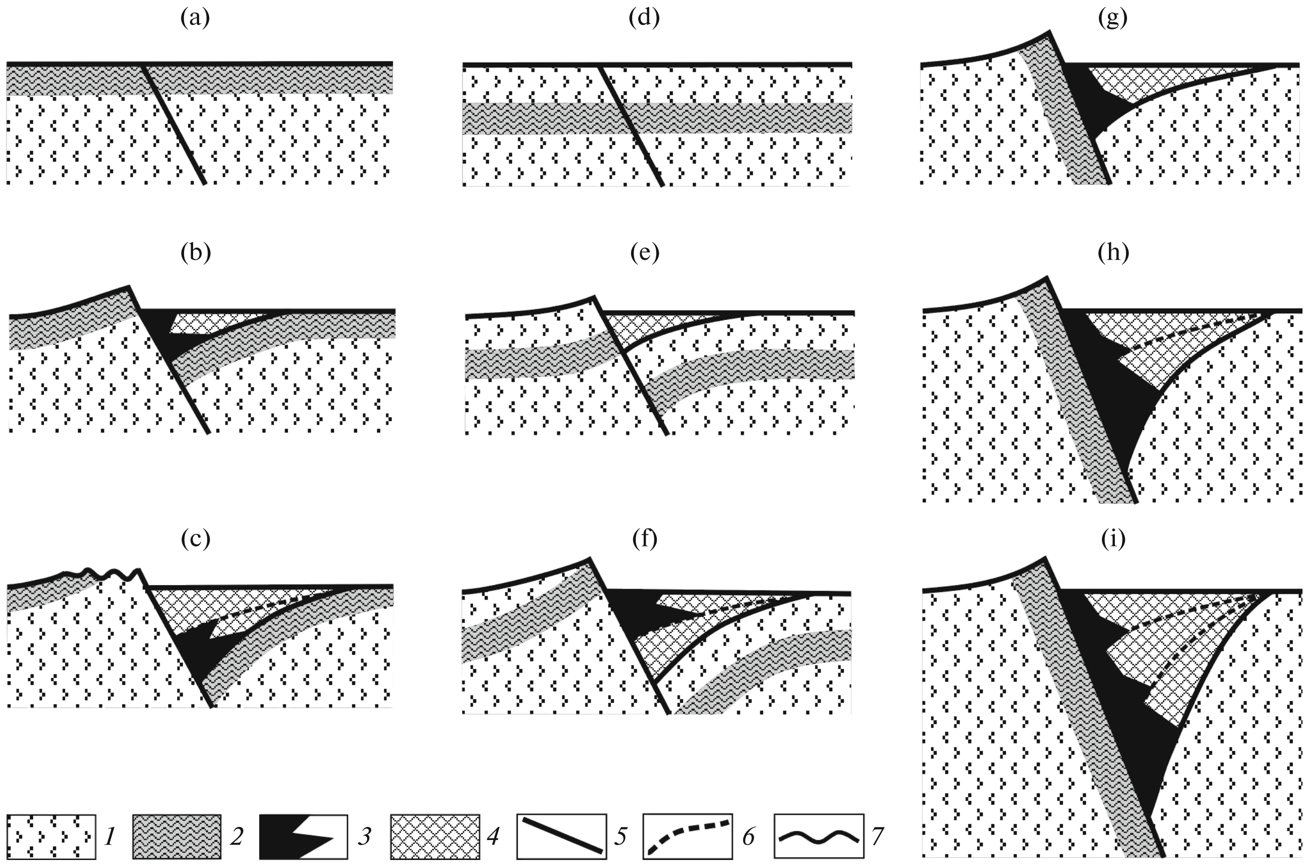

Fig. 5. Models of graben formation and respective types of epidote-rich intervals: Molokovo (a–c), Bobrovo (d–f), Roslyatino (g–i). (*1*, *2*) Basement: (*1*) amphibolites and migmatites, (*2*) blastomylonites containing crystalline epidote; (*3*) detrital epidote from blastomylonites in heavy sandstone fraction; (*4*) arkose deposits from outer source; (*5*) normal faults; (*6*) intermediate surfaces of graben bottom; (*7*) erosional boundaries.

Bobrovo-type intervals, characterized by epidote input from a local source at the late stages of the graben's evolution, is caused by the subsided position of the blastomylonite layer by the moment of the normal fault forms (Fig. 5d). In this case, rocks of the upper slab (amphibolites and plagioclasites) occur at the base of the graben. Further subsidence of the graben is accompanied by its compensation with sediments, without enrichment in erosion products from the blastomylonite layer (Fig. 5e), the influence of which is manifested at the late stages of the graben's growth (Fig. 5f).

Roslyatino-type intervals, with enrichment in epidote through the entire sedimentary sequence, forms with a steeply occurring blastomylonite layer and normal fault development along its dip (Figs. 5g–5i). Subsidence of the basin, accompanied by uplift of the footwall, not only did not lead to isolation of the blastomylonite layer, but, on the contrary, it constantly stimulated an intensive supply of epidote from this local source.

The relationships between strata in the orientation of Neoproterozoic normal faults and Paleoproterozoic blastomylonite layers also determined the tectonic–sedimentary evolution of sedimentary basins. In the case of cutting normal faults, especially if blastomylonite layers occur at low angles, the grabens that formed had a rheologically determined subsidence limit (Molokovo type). Here, subsidence of granitoid rocks into the denser amphibolite substrate was limited by isostatic equilibrium forces. With an unchanged regional stress field, grabens of this type underwent lateral expansion after attaining a certain limit of subsidence, and this led to accumulation of regressive sedimentary sequences with the irreversible transition from lacustrine to alluvial–proluvial deposits. This type of grabens is characteristic of one-time manifestation of a local source of clastic material, independently of the stage of structural evolution. The occurrence and evolution of normal faults along blastomylonite layers (Roslyatino type) was energetically more efficient and did not disrupt the isostatic equilibrium, leading to the formation of deep narrow grabens in which the sedimentation environments did changed radically with time. Epidote continued to be supplied during the entire period while accommodation existed, because progressive subsidence of the graben constantly triggered the activity of its local source.

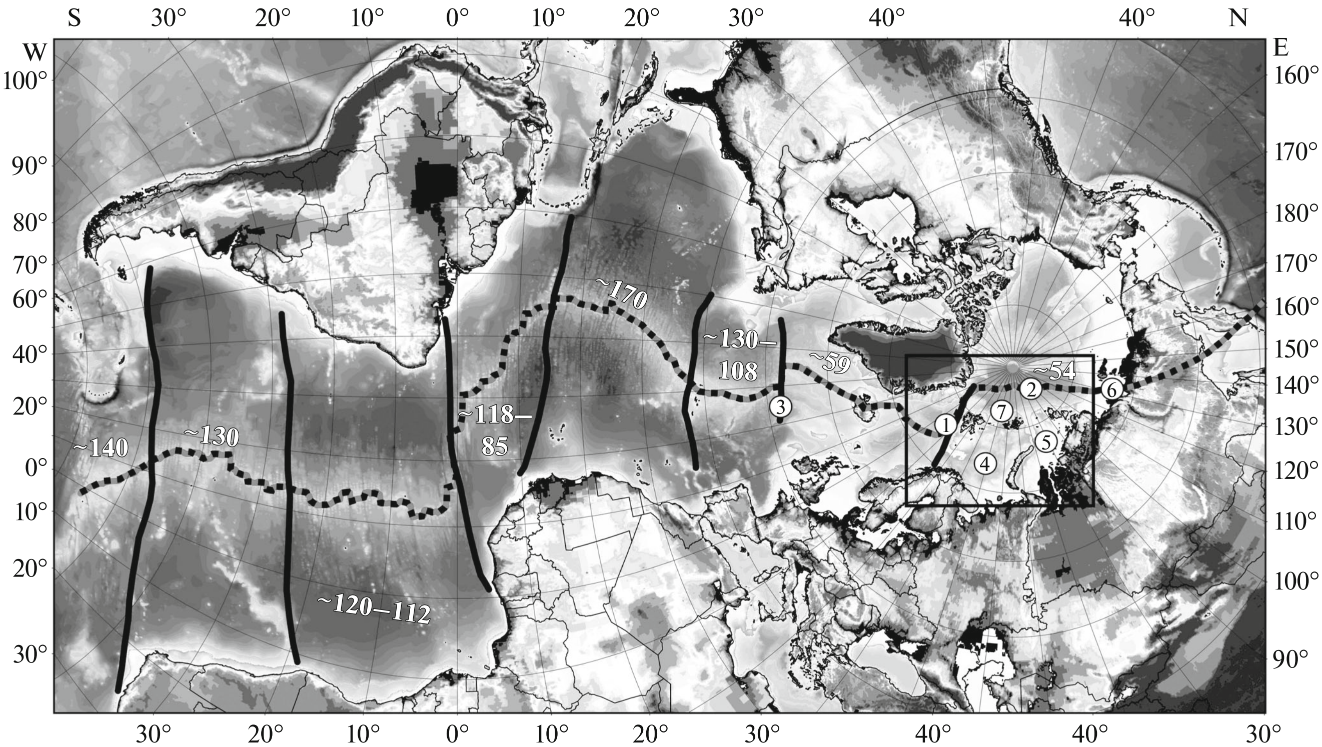

Fig. 6. Atlantic–Arctic rift system (AARS). Black rectangle denotes location of Western Arctic megaprovince; dotted line, AARS profile along which values of *Vp/Vs* ratio were calculated. Segmentation of AARS into blocks (thick lines orthogonal to MAR) is given for onset time of spreading in them, Ma ago (numerals). Encircled numerals: 1, Knipovich rift; 2, Gakkel rift; 3, Charlie Gibbs Fracture Zone; 4, Barents Sea; 5, Kara Sea; 6, Laptev Sea; 7, Franz Josef Land.

SUPRAREGIONAL SYSTEMS

This type of tectonic–sedimentary systems includes megaprovinces which represent large components of crustal segments (Fig. 1). Study of these complex polygenetic objects is not only key for understanding the present-day tectonics and geological evolution of large territories, it also makes it possible to estimate the direction of their evolution in time.

West Arctic Megaprovince

This megaprovince is the junction of two oceans, the Atlantic and Arctic, and incorporates two provinces, the Norwegian–Greenland and Eurasian (Barents Sea–Kara Sea). Both provinces are coupled links of the joined Atlantic–Arctic chain of rift structures (Fig. 6).

The main structural elements at the boundary between the two provinces are the Knipovich rift and Molloy Fracture Zone, which join the Gakkel rift almost orthogonally. This type of structural junction reflects the general pattern in the relationships between Atlantic–Arctic rift structures. For example, in the central polar projection, sinistral strike-slip faults can clearly be seen (Knipovich Rift valley and Charlie Gibbs Fracture Zone), which are subparallel to each other. Arctic fractures are subparallel to Atlantic transform faults (also sinistral strike slip or neutral), which determine the outlines of the African and American continents. Rifting processes have completely determined and continue to determine the evolutionary patterns of the lithosphere, the scales and morphology of forming structures, and the character of accumulation and transformation of sedimentary cover complexes in the megaprovince. Extension in the Norwegian–Greenland province took place in the Late Devonian and Carboniferous in Norway and eastern Greenland [29, 32, 37, 38]. According to the reconstructed movement of Greenland relative to stable Europe, the most intensive phase of opening in the Norwegian–Greenland province was in the Eocene, about 55–33 Ma ago (magnetic anomalies 24–13) [46]. Opening of the northern region of the province began ca. 33 Ma ago (magnetic anomaly 13), when Greenland and Eurasia separated from each other [36, 43]. The Eurasian province is presently the youngest and tectonically active link in the series of Arctic rift structures.

New original data obtained during field studies in the territories and water areas of the megaprovince have made it possible to characterize its main structural features and outline the contour of a comprehensive tectonic evolution model [12, 18, 20–23, 26]. Analysis of the travel times ratios and shear seismic waves and their comparison with the characteristics of the mantle medium according to seismic tomography

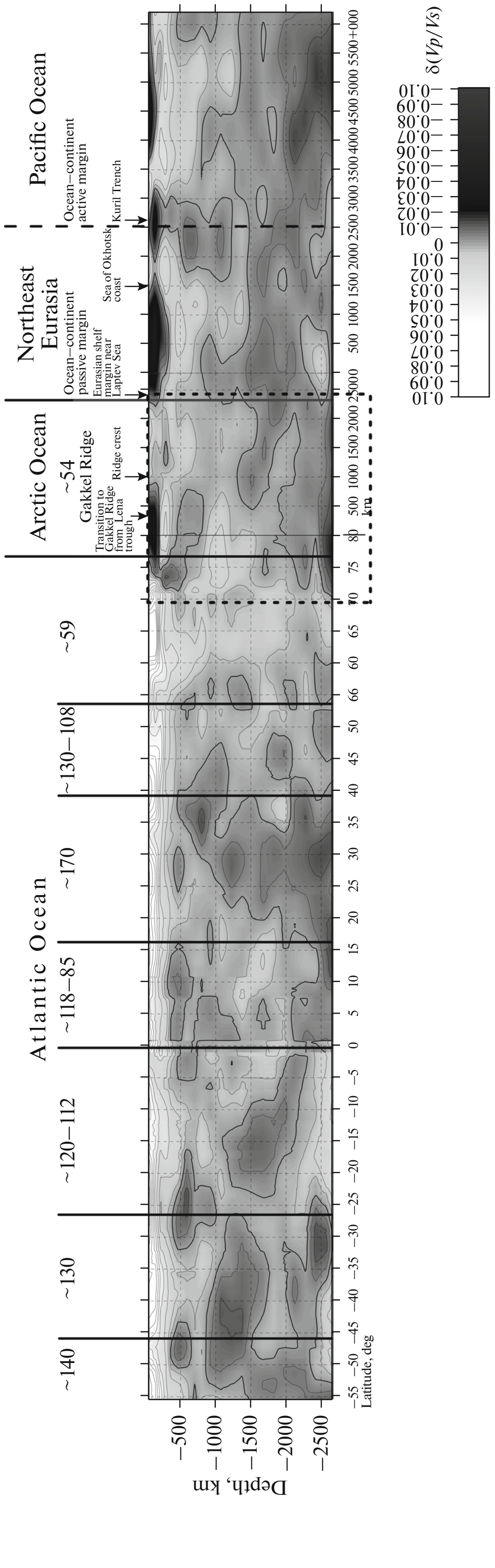

Fig. 7. Profile along AARS with depth distribution of $\delta(Vp/Vs)$ parameter calculated from data of [31, 47] by technique described in [22]. Dotted rectangle indicates region of Western Arctic province. Position of AARS profile is same as in Fig. 5. Transect from 55° S to 80° N is shown in projection to latitude axis, then across pole, and along profile line with horizontal coordinate (km). Vertical lines denote block boundaries (dividing faults) with indicated onset time of spreading.

data allowed us to estimate the variations in rifting intensity [20].

It has been found that the megaprovince is part of the Atlantic–Arctic rift system, which is a planetary-scale structure at least 18000 km long, which includes the Mid-Atlantic Ridge (MAR) and Gakkel Ridge (Fig. 6). The general evolutionary trend of the Atlantic–Arctic rift system is directed from south to north. The age of onset of spreading processes in different segments of this system ranges from 170 Ma in the Central Atlantic megaprovince to 54 Ma in the Atlantic–Arctic rift system (Fig. 7). This age difference indicates that the Atlantic–Arctic rift system is not a united divergent boundary with a closed convective cell covering the entire mantle.

The direction of extension from south to north across the North Pole leads to an orthogonal junction between the growing extension zone of the Gakkel Ridge and continental massif of northeastern Eurasia. Progradation of the rift system is accompanied by the formation of immature branches, so continental breakup along them ceased without the formation of large basins. The Russian segment of the megaprovince includes two regions where the rift interacts with the structural continental barrier: the Laptev Sea and Franz Josef Land. In the context of the Atlantic–Arctic rift system's evolution, both these regions (as well as the deep part) are of certain value as objects of (1) rift tectogenesis that ended in the Lower Cretaceous and (2) present-day tectogenesis whose trajectory across northeastern Russia, via interaction with the continental plate, has not yet been defined.

Tectonic Prehistory of the Western Arctic

Generalization of interdisciplinary data indicates that the tectonic prehistory of West Arctic megaprovince began in the Neoproterozoic. The possible mutual positions of continental landmasses in the Precambrian have been analyzed in many publications, and their generalized meaning has been verified by recent study [33]: in the period from the Late Paleoproterozoic to the Middle Neoproterozoic, the East European, Laurentian (North American), and Siberian megaprovinces were parts of the Columbia supercontinent.

The existence of a united massif of continental crust in the past allows the possible continuation of the

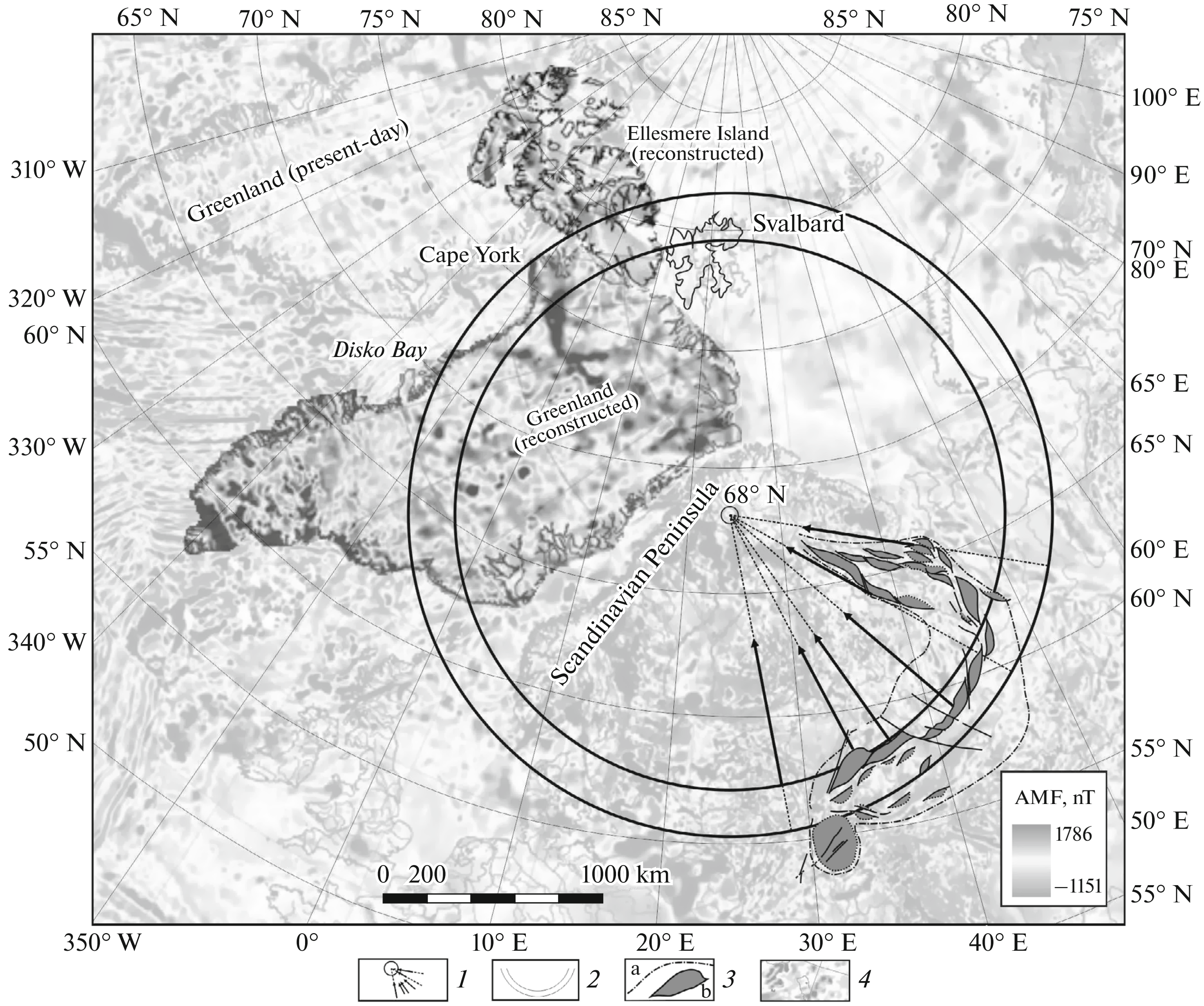

Fig. 8. Palinspastic reconstruction of boundaries of Neoproterozoic supraregional geodynamic system based on anomalous magnetic field (AMF) data [19, 34]. (*1*) Convergence point and projections of lines orthogonal to orientation of Middle Russian aulacogen and Polotsk–Kurzeme fault belt, but parallel to orientation of main structures of Belomorian–Pinega region; (*2*) search circle; (*3*) main tectonic–sedimentary systems: (a) preplate, (b) plate; (*4*) fragment of AMF total vector map in terms of present-day geography, in polar projection, with center of least distortion at 68° N, 25° E.

Middle Russian–Belomorian province to be traced. We suppose that structures of the Middle Russian–Belomorian tectonic couple characterize a small part of the supraregional system, a considerable part of which was reworked during the Paleozoic–Cenozoic formation of the present-day Western Arctic megaprovince. Using the patterns of spatial positions of the Middle Russian–Belomorian structures, we can draw the contours of supposed paleogeodynamic system (Fig. 8). The inset shows the azimuthal directions of the main structural elements in the Middle Russian–Belomorian tectonic couple. Projections of axes of Belomorian–Pinega troughs and normals to tangential lines relative to the arcuate Middle Russian aulacogen yields an overall convergence at about 68° N, 25° E. Understanding that determination of the true Euler pole requires special calculations, let us conditionally consider this point as an instant pole of rotation for the Middle Russian–Belomorian tectonic couple.

Assuming the geometric point of convergence to be the center of a circle, we can outline tectonic–sedimentary systems that could potentially participate in the united Neoproterozoic geodynamic process along the circle proper. In order to reduce errors caused by surface curvature, our constructions were carried out on a map of the total magnetic field vector in the polar projection, with the coordinates of the point with minimal distortions corresponding to the geometric point where the azimuths of orientation of the main structures converge (Fig. 8).

Palinspastic reconstruction of the positions of Greenland and Ellesmere Island in the Neoproterozoic (Late Riphean) according to sequential "closure" of magnetic anomalies on the map of total anomalous magnetic field vector agrees with the reconstructions in [30, 35]. The region of highest interest is the band confined by radii about 1200 and 1500 km long, which were assumed on the basis of the observed transverse sizes of the Middle Russian aulacogen. Within this zone, about 300 km wide, the sought Neoproterozoic tectonic–sedimentary systems or relicts thereof may be located in relatively observable territories that belonged to the ancient Euro-American Craton.

In Western Europe, the reconstructed paleogeodynamic system most likely included expanding strike-slip structures of Gotland Island and the southern Scandinavian Peninsula. Interpretation of DSS data showed that there is a localized trough in the Moho surface beneath the central Baltic Sea: this trough is up to 45 km deep and 110 km wide, bounded by stepwise normal faults up to 2–3 km, and spatially extends northwestward [39, 40]. In other words, there is the tectonic belt in the central Baltic Sea extending about 500 km NW–SE from the eastern coast of southern Sweden, through the northern part of Öland Island, and completely encompassing Gotland Island. On the eastern coast of the Baltic Sea, it runs to the south of the Riga rapakivi pluton and enters the western part of the Polotsk–Kurzeme fracture belt, which is thought to be a continuation of structures in the Middle Russian region. Although the nature of this belt is yet unclear, it is interpreted as either a Neoproterozoic rift or relict of the ancient continental margin [7].

The belt with a semitransparent pattern of magnetic field extends into the territory of Greenland, in parallel to the search circle. This type of magnetic field is characteristic of zones where consolidated crust has been reworked and revealed, in particular, along the extent of the Middle Russian aulacogen. Given that the search band is a geometric abstraction and taking into account certain unavoidable distortions and uncertainties (primarily related to the final position of Greenland relative to the European Platform with respect to Caledonian sheets), we can quite confidently state that the formation of the Greenland zone of the transparent magnetic field is related to the reconstructed Neoproterozoic geodynamic system.

The rocks revealed within the circle include (1) migmatite gneisses that underwent plastic deformation, containing interbeds and boudins of amphibolites, and (2) unmetamorphosed red sandstones, resting unconformably on eroded granites and pertaining to the Gardar (ca. 1 Ga ago) tectonic stage [11]. It can be suggested that migmatized gneisses of the Egedesminne complex correspond to tectonic mélange rocks in the basement of the Middle Russian–Belomorian province, whereas red psephytes can be compared to coarse-grained rocks from the red-colored sequence of the Molokovo Series. The arguments for the latter are both facies signatures of rocks and the Gardar (Late Riphean) age of sandstones.

The geological data indicate that there were tectonic–sedimentary systems within the search circle and along its nearest periphery in the Neoproterozoic, the formation of which was dominated by brittle extension regime on blastomylonite zones. This is supported by the suggestion about possible formation of strike-slips and associated basins, geodynamically coupled with those of the Middle Russian–Belomorian province, in the Neoproterozoic in the territories of present-day Western Europe, Greenland, Ellesmere Island, and, probably, northern Svalbard.

The observed relationships between structural elements, on the one hand, and different directions of shear motions in the tectonic couple, on the other, were most likely determined by asymmetric vertical movements of the Baltic geoblock and its frame. Relative uplift of the Baltic geoblock in the vicinity of the Onega High, where the directions of the axes of the main extension systems within the tectonic couple sharply change, led to the formation of differently directed shear motions relative to the elements of the outer and inner surfaces: right-lateral strike-slip appears to the northeast, while right-lateral strike-slip, to the southwest.

On the scale of the East European Platform, the abrupt bend of the Middle Russian–Belomorian belt in the area of the Onega High reflects the general arrangement pattern for a series of arcuate structural zones (with their convex parts oriented to the southeast of the Baltic geoblock): (1) the Mezen–Vychegda, which gradually transitions into the Moscow, (2) the Kama–Vyatka, and (3) the Ryazan–Saratov, which is coupled with the Tokarevsko–Ufa and Osa [9]. It can be suggested that these asymmetric series of different size reflect different uplift stages of the Belomorian geoblock (like annual tree rings) and/or gradual subsidence of its southeastern frame. In this case, we suggest that the tectonic–sedimentary systems in Western Europe, Greenland, and North America are reflections of these movements in the periphery of the geoblock.

Perspectives of Tectonic Evolution

Study of the structures of megaprovinces coupled with analysis of their spatial locations and relationships with adjacent areas makes it possible to address the evolutionary trends of the largest supraregional tectonic–sedimentary systems (crustal segments).

The regular distribution of the Atlantic–Arctic rift system over vast areas from south to north during a long period of geological time indicates the global character of this phenomenon. Present-day fading of the Gakkel rift in the Laptev Sea seems to be a temporary event. Based on analysis of the spatial distribution of seismicity, one should expect progradation of this rift system through the structures of the Omolon and Verkhoyansk belt toward Deryugin Bay (Sea of Okhotsk) or southern Kamchatka (Fig. 6) [20].

Precisely to how it took place with the more ancient parts of the Atlantic–Arctic rift system, its continuation intersects areas (megaprovinces) of different age and genesis, from divergent Arctic areas, through the northeastern zone of epiplatform orogeny, to the marginal seas of the West Pacific.

Following the pattern of rift development, the subsequent evolution of territories is determined by postrift subsidence and expansion of syneclises, like what took place during the geological evolution of the Neoproterozoic–Paleozoic Middle Russian–Belomorian province. The only difference is the supraregional (planetary) scale of the process. The object affected by rifting is not a particular zone, but a set of megaprovinces. This process is now taking place in the Arctic region: the water area of the Arctic Ocean exceeds by many times the extents of rift structures proper; however, in the first approximation, it outlines the boundary of a growing syneclise.

From the viewpoint of the contemporary and expected evolution of the Atlantic–Arctic rift system, zones characterized by different basement structure, time of main folding, and foundation of the plate cover become one structure. Such integration of heterogeneous megaprovinces is likely caused by a number of geological and cosmological processes. From the viewpoint of mechanics and kinematics, the integration of heterogeneous segments seems to be the necessary condition for transfer and propagation of deformations.

Earlier analysis of the structure and spatial distribution of continental platform regions with different ages revealed that the evolution of these regions implied accretion of ancient platforms at the expense of younger ones [4, 6]. Matured platform regions consist of the main segments of two types: epi-Baikalian (matured) platforms proper and ancient platforms. Young platform regions incorporate young (epi-Paleozoic with epi-Cimmerian zones) platforms proper, mature platforms, and ancient platforms. Juvenile (epi-Mesozoic) platform regions consist of segments of different age: young, mature, and ancient.

Our data verify these conclusions and develop them further. In particular, the revealed evolutionary series can be logically finished by recent (neotectonic) platforms. Within Eurasia, which is the largest present-day continent on Earth, the Eurasian platform zone can be distinguished. Recent tectonic movement within its limits took place in the Late Oligocene–Quaternary, and the vast region where these movements occurred in this time period is consistent with what is called a platform (i.e., a region with predominantly flat relief and with a geological section containing both a basement composed of folded metamorphosed rocks and a cover composed of relatively undisturbed sedimentary and volcanogenic rocks which did not undergo regional metamorphism).

Within the Pyrenean and Crimea–Caucasus–Kopet Dagh overlapping fold systems, basins of deep seas underlain by suboceanic crust (Black Sea and South Caspian) are situated at the boundary of the platform. In the north and northwest, the platform is bounded by the oceanic megaprovinces of the Bay of Biscay and Arctic Ocean. In the south, southwest, and southeast, the platform is bounded by extensive orogenic zones: overlapping folded megaprovinces of the Alpine–Himalayan mobile belt (Pyrenees, Alps, Carpathians, Crimea, Caucasus, Kopet Dagh, Pamir-Alay) and megaprovinces related to epiplatform orogeny (deutero-orogenesis; the Tien Shan, Dzungarian, Altai–Sayan, and Verkhoyansk–Kolyma mountain systems). Thus, the recent Eurasian platform zone occupies the majority of the land part of northern Eurasia and a considerable area in the offshore zones of the North, Norwegian, Barents, and Kara seas.

Recent orogenic rises bordering on the platform significantly affected adjacent plate structures. For example, under the effect of the uplifted structure of the Alpine–Carpathian orogen, the Central European zone of rises formed in parallel to it. The ongoing evolution of the Atlantic–Arctic rift system led to the occurrence of recent rifts (like the Rhine rift) within the platform; in addition, the East Baltic rift system formed during the last 0.4 Ma in the Baltic Sea region.

The recent Eurasian platform zone can be extended if we consider the Moma rift zone as an intraplatform unit. In this case, the zone of the Mesozoides in northeastern Asia can be included in the recent Eurasian platform. In addition, we can expect that the recent Eurasian platform will expand southwards and eastwards. Indeed, intermontane basins of the megaprovince related to epiplatform orogeny (deutero-orogenesis) in the Asian part of the Eurasian lithospheric plate are tectonic–sedimentary systems with thick epi-Mesozoic volcano-sedimentary covers. Although these structures are at the initial stages of their evolution (from the viewpoint of the evolution of platform regions), they can be conditionally included in the recent platform of the Central Asian megaprovince related to epicollision orogeny.

This also applicable to tectonic–sedimentary provinces in the Asian part of the Pacific mobile belt. After termination of the active evolutionary phase, marginal seas, which evolved as a result of intensive extension in back-arc areas, will become polygenic syneclise-like basins with a rift basement pertaining to the preplate (active) stage of evolution and volcano-sedimentary cover of the plate.

The mentioned characteristics of the recent platform have resulted from integration of heterogeneous megaprovinces, whereas the Eurasian platform is thought to be the main region where present-day geodynamic processes, controlled by planetary-level patterns, are realized.

DISCUSSION

The proposed classification of tectonic–sedimentary systems allowed us to order the studied objects according to the extent geological processes are manifested and, in some cases, to revise the parameters of these processes for assessing the tectonic setting. First of all, this is applicable to sedimentary basins: reassessment of their scale and role played in the structure of the tectonosphere has generated a tendency to consider them as some universal indicator of geodynamic regimes. In terms of the united systemic approach to this analysis, tectonic–sedimentary systems have been considered records of the geological history for locally and regionally ranked structures and the evolutionary direction of genetically and historically different megaprovinces and crustal segments. On this basis, we obtained original results, of which the most important are the following.

The present-day state of the Middle Russian–Belomorian province is the result of interaction between regional and local tectonic and sedimentary processes in the continental crust, with the scales of the formed lithological complexes and their positions in the crust reflecting the ranks of tectonic–sedimentary systems. Lithological complexes of local systems are confined to levels of upper crust or sedimentary cover, whereas regional systems involve the entire crust.

The regional drivers of these processes radically change at different stages in a province's evolution; however, the area of their manifestation remained unchanged during a long-term period of geological time (hundreds of millions of years). The organization of lithological complexes does not reflect the direct inheritance of tectonic processes, but, in to a large degree, their predetermination by geodynamic events of the preceding stages (tectonic prehistory) of tectonic–sedimentary systems. For example, petrophysical properties of Paleoproterozoic crust predetermined the zone where rifting manifested in the Neoproterozoic. Development of regional strike-slip faults in the crust controlled the evolution of extension systems at the preplate stage. The appearance of a rigid massif on the propagation path of a regional strike-slip fault in the Middle Russian region led to transfer displacement of the axis of the aulacogen, which in turn predetermined the structural asymmetry of the main plate structure (Moscow syneclise). The inhomogeneous properties of the consolidated crust (caused by Paleoproterozoic tectogenesis), combined with Neoproterozoic rifting, predetermined the selective location and growth patterns of the Soligalich megaswell during the entire Phanerozoic history of subsidence of the syneclise.

Local inhomogeneities in the basement structure determined its response to the application of regional tectonic stresses and controlled the formation genetically similar, structurally isolated near-fault grabens. With an overall general similarity of processes, each graben was an independent tectonic–sedimentary system, and this is reflected in individual facies features of its sediment fill complexes.

Among the fundamentally important results, we should mention the principle of minimal energy costs in the realization of dynamic processes. For example, beginning from their occurrence, all preplate tectonic–sedimentary systems in the Middle Russian–Belomorian province evolved within a band of migmatized and dynamically reworked crust.

During further structural formation in both extension systems of the Middle Russian–Belomorian tectonic couple, crustal faults and associated basins aligned with the available space within the brittle upper crust; they branched to "bypass" large tectonic (Arkhangelsk and Torzhok) massifs, but afterward, they tended to restore their alignment along the axis of the main strike-slip fault.

The principle of minimal energy costs also agrees with the regular degeneration of basin-forming Neoproterozoic deep detachments owing to the accommodation to more ancient detachments. The revealed mismatch (in plan view) between brittle structures (sedimentary basins) and thinned portions of crust indicates a secondary character of thinning. The orientations of axes of thinned portions of crust are discordant with those of structures in both the Belomorian–Pinega and Middle Russian regions. This suggests that the redistribution of middle- and lower-crustal masses, caused by a large-scale strike-slip fault, also occurred following the principle of least energy cost with a clear tendency toward straightening of the deformation vectors.

The considered pattern of dynamic processes is also manifested at the local level. The orientations of Neoproterozoic normal faults and oblique strike-slip faults (with a normal fault component) do not coincide with the orientation of Paleoproterozoic strike-slip zones or schistosity of the metamorphic basement. Young faults tend to align with ancient zones in weakened crust. When the Neoproterozoic normal fault plane matches the Paleoproterozoic detachment plane (blastomylonite layer), deep dynamically evolving sedimentary basins appear.

Study of the Western Arctic megaprovince has revealed the evolutionary patterns of large (supraregional) rift systems. It has been found that the studied megaprovinces are parts of a global-level structure (Atlantic–Arctic rift system). The formation of the system cannot be related to a closed convection cell in the mantle because of the directed rejuvenation of spreading processes along its trend from south to north. The fundamental hypothesis explaining this tectogenesis scenario along the Atlantic–Arctic rift system concerns crustal extension as a response to drifting plates. The combination of these factors determined the time, location, and character of spreading processes, formation of oceanic basins, and occurrence of basins in adjacent continents with thick sedimentary sequences.

The tectonics of the Knipovich rift formed from the combination of right-lateral strike-slip displacements. These form the present-day structure of the Knipovich rift area as a local rift in pull-apart settings [23]. The logical trend of the tectonic evolution for this segment of the Atlantic–Arctic rift system suggests that it will most likely be transformed into a unified strike-slip fault oriented perpendicular to the main spreading centers (Mona and Gakkel ridges). This scenario is supported by tectonic activation of the southeastern flank of the Knipovich rift (asymmetric distribution of weak earthquake epicenters) and the character of faults in the upper sedimentary crust on the eastern flank. This strike-slip fault should evolve with a tendency toward maximal straightening of the transfer zone between segments of the Atlantic–Arctic rift system.

Of special interest is the possible scenario of further evolution of an orthogonal junction between the growing extension zone of the Gakkel Ridge and the continental massif of northeastern Eurasia. Based on the revealed patterns in the evolution of the Atlantic–Arctic rift system and assuming that the principle of least energy cost is in effect during dynamic processes at all levels of crustal structures, we suggest that the further evolution of this rift system will be directed toward the Sea of Okhotsk and corresponding structures. The argument for this is the presence of a seismically active zone joining rift structures in the Laptev Sea (Gakkel–Omolon) and Sea of Okhotsk (Deryugin Basin).

An important result of our studies is the following conclusion: realization of large-scale geodynamic processes is preceded by a decrease in the heterogeneity of geological setting, which can be described, in terms of tectonic–sedimentary analysis, as an integration of megaprovinces. Integration of heterogeneous segments into a conditionally unified body (platform region) is thought to be the necessary condition for geodynamic processes at recent stages.

Integration of heterogeneous megaprovinces is expressed in the regular accretion of ancient platforms at the expense of younger structures. It is this pattern that allowed us to substantiate a recent platform region in Eurasia —a vast domain where modern geodynamic processes controlled by planetary-level patterns take place.

The idea about further southward expansion of the Eurasian platform region at the expense of structures of the Central Asian megaprovince related to epicollision orogeny is supported by the fact that the mentioned megaprovince incorporates large intermontane basins with thick epi-Mesozoic volcano-sedimentary covers. The eastward progradation of the recent platform region can occur in the future via the inclusion of tectonic–sedimentary provinces in the Asian part of the Pacific mobile belt. After termination of the active evolutionary phase, marginal seas, which evolved as a result of intensive extension in back-arc areas, should become polygenic syneclise-like basins with a rift basement pertaining to the preplate (active) stage of evolution and plate volcano-sedimentary cover.

A similar process is currently happening in the Arctic Basin, where the total water area of the Arctic Ocean significantly exceeds the extents of rifting structures proper, but it outlines, in the first approximation, the boundary of a growing syneclise.

CONCLUSIONS

The different orders of structure-forming processes determine the hierarchical organization (intersubordination) of tectonic–sedimentary systems describing structural–morphological zones with different extents. For example, the evolution of systems on the scale of lithospheric plates is related to global tectonics, while the evolution of provinces and parts thereof are governed by regional tectonic processes.

Independently of rank and geodynamic level of tectonic–sedimentary systems, at all levels (from local to supraregional), geological processes occur following the principle of least energy cost.

Comparative analysis of tectonic–sedimentary systems corresponds to the general tendency of developments in earth sciences and is aimed at obtaining quantitative estimates of processes and phenomena in the transition from describing to developing integrated forecast models. Interdisciplinary studies of multicomponent systems include (1) revealing the drivers of structural formation, (2) estimating the scales of tectonic and sedimentary processes, and (3) reconstructing ancient tectonic–sedimentary systems and searching for their possible present-day counterparts.

Integrated tectonic–sedimentation models possessing predictive features should take into account the relationships between the extents and spatial locations of areas where geodynamic processes occur (tectonic–sedimentary systems), as well as the resultant geological bodies.

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