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Structure and Stages in Development of the Cataplatform Cover in the Central Russian–Belomorian Province

N. P. Chamov

Geological institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia
e-mail: nchamov@yandex.ru

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Abstract—The results of correlation between seismic sequences (based on the CMP data) and lithostratigraphic units (based on drilling data) of the preplate sedimentary section are discussed. By the structure and interrelations of seismic sequences, as well composition and facies features of lithological varieties, three successive stages in the formation of the cataplatform cover of the province are recognizable: (1) main stage of the graben formation in the Central Russian and White Sea–Pinega regions; (2) terminal stage of the graben formation–initial stage of postrift subsidence in all regions; (3) the formation of a 'protosyneclise" (non-riftogenic depression) in the Orsha region. The model for explaining the formation of the Orsha depression is proposed.

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GEOLOGICAL POSITION, STUDY HISTORY, AND EXISTING PROBLEMS

The Central Russian–Belomorian province (hereafter, CBP or Province) is located within the ancient East European Platform (EEP) and comprises a region extending from Kandalaksha Bay of the White Sea to upper reaches of the Volga, Dnieper, and Zapadnaya Dvina rivers (Fig. 1). It is a complex polygenic megabasin, which was developing since the Neoproterozoic till the Late Phanerozoic and structurally evolving from the riftogenic zone to the mature platform.

Two structural megacomplexes take part in the sedimentary cover of the Province: (1) cataplatform (Lower Baikalian of the Upper Riphean–Lower Vendian); (2) orthoplatform (Upper Baikalian, Caledonian, Hercynian, and Cimmerian–Alpine of the Upper Vendian–Quaternary (Garetskii, 1995; Garetskii and Nagornyi, 2011).

The cataplatform development stage is of particular interest owing to the diversity of tectono-depositional settings. The major strike-slip displacements in the craton body, which determined the region development at that time, resulted in the formation of peculiar extension structures: grabens and aulacogens. Its termination culminated in grandiose tectonic reorganization at the Early–Late Vendian boundary: transition from the riftogenic destruction of the craton to its stabilization and the formation of plate cover in spacious subsidence regions. The change determined both the trend of the further structural and geomorphological development of the continental block and the distribution of mineral resources within its limits.

The cataplatform structural complex unites tectono-depositional systems sandwiched between Proterozoic metamorphic rocks of the platform basement and rocks of the orthoplatform cover. They are usually represented by fault-line grabens, which frequently form extended chains confined to axial areas of the Province (Fig. 1).

The complex is overlain by rocks of the orthoplatform cover, the base of which is composed of Upper Vendian (mostly clayey) rocks of the Redkino Formation. Owing to petrophysical properties of these rocks, the boundary between megacomplexes of the sedimentary cover of the platform is readily recognizable in logs as a "high-resistance horizon."

Based on orientation of basement structures and spatial position of main cataplatform tectono-depositional systems, three regions are distinguishable in the Province: southwestern (Orsha), central (Central Russian), and northeastern (White Sea–Pinega) (Chamov, 2016).

Despite the theoretical and practical interest of geologists to rocks of the cataplatform cover since the 1940s, many aspects of its structure remain debatable. This is primarily explained by low density of the network of seismic profiles and deep wells. Moreover, the Riphean–Vendian section is recovered by single wells.

The structure, depositional environments, and economic potential of the cataplatform cover remain the most important problems in lithology of this region. The most complex among them is the age of

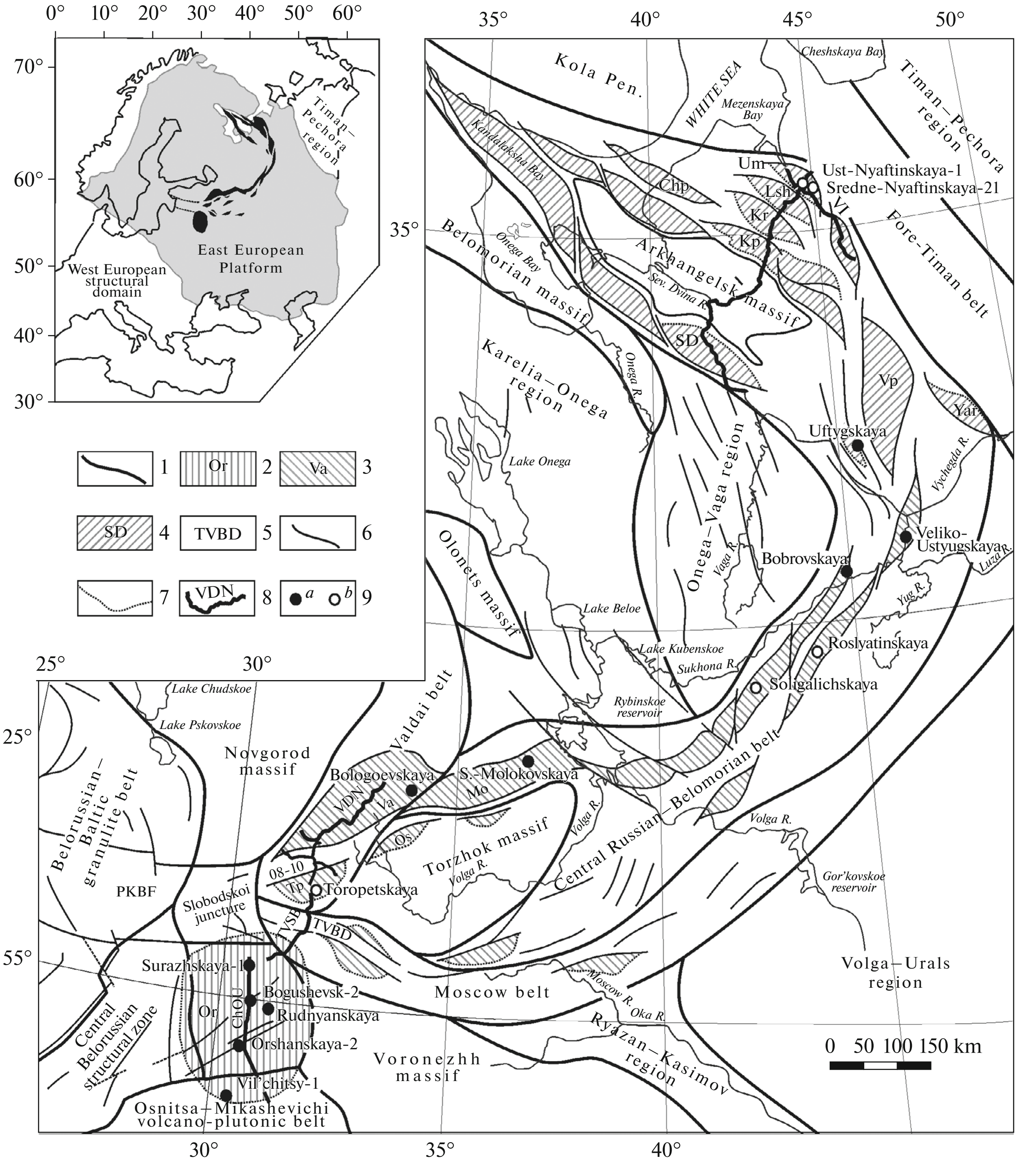

Fig. 1. Preplate tectono-depositional systems of the Central Russian–Belomorian province.
(1) Boundaries of lithotectonic complexes of the basement; (2–4) preplate tectono-depositional systems of regions in the Province: (2) Orsha: (Or) Orsha depression, (3) Central Russian—grabens: (Va) Valdai, (Tp) Toropets, (Os) Ostashkovo, (Mo) Molokovo, (4) White Sea–Pinega—grabens: (SD) Severnaya Dvina, (Kp) Kepa, (Kr) Kerets, (Lsh) Leshukon, (UM) Ust-Mezen, (Chp) Chapoma; (5) belts of faults and deformations: (PKBF) Polotsk–Kurzem belt of faults, after (Garetskii and Karataev, 2009), (TVBD) Toropets–Velizh belt of deformations, after (Kostyuchenko et al., 2008); (6) faults, proven and assumed, after (*Razlomy* ..., 2007; Chamov, 2016); (7) line indicating pinching out of the sedimentary infill of basins; (8) seismic CMP profiles: (ChOU) Cherikov–Orsha–Usvyaty (*Razlomy* ..., 2007), (TVSB) Toropets–Velizh–state boundary (Kostychenko et al., 2008), (VDN) Valdai–Deminsk–Nakhod (Kostychenko et al., 2007); (9) Well, after (*Gipsometricheskaya* ..., 2001): (*a*) reaching the crystalline basement, (*b*) abandoned in Riphean sedimentary rocks.
Inset: position of preplate tectono-depositional systems in the structure of the East European Platform.

sediments in the isolated grabens and troughs. Uncertainty in the structural interrelations of cataplatform tectono-depositional systems makes the correlation of Riphean–Lower Vendian sedimentary successions an extremely difficult task. With reselect to these problems, researchers always asserted different opinions and put forward different variants for their solution. Therefore, many questions concerning age of the formation, interrelations, and tectonic nature of the main Neoproterozoic structures in the Province (Central Russian aulacogen, White Sea–Pinega grabens, and Orsha depression) remain topical.

The purpose of this work is to accomplish seismofacies description and correlation of elements of the cataplatform section within both main regional structures and the Province as a whole.

For this purpose, seismic sequences were defined in the seismic CMP records. These sequences differ from each other by extension, inclination, and dynamic intensity of the bounding and internal reflections. The seismic data are correlated with drilling results and the seismic sequences are correlated with lithostratigraphic units of the cataplatform cover. Position of seismic sequences in the section and facies analysis of their sediments made it possible to define stages in the formation of elements of the cataplatform cover and corresponding tectono-depositional settings.

RESULTS

Seismic Facies of the Cataplatform Cover

The **seismic sequence $\mathbf{R_3^4}$or**[1] is developed through the entire Orsha depression (Fig. 2). It characterizes the upper part of the preplate or cataplatform cover.

In the ChOU profile section, the seismic sequence is characterized by beaded structure owing to the convergence and divergence of its upper and lower boundaries. Inside the sequence, reflections are distinct but wavy, discrete, and nonconformal with any bounding surfaces. The general shape of reflections indicates wide development of lenticular structures and frequent pinchouts. Gently dipping southward reflections, which are characteristic of the bounding surfaces of clinoform sedimentary bodies, are relatively well traceable. Three seismic members (R_3^{4-1}–R_3^{4-3}), relations between which imply progradational (from the north to south in the profile section) sedimentation, can be defined conditionally in this seismic sequence (Fig. 2).

Analysis of the seismic exploration data on the ChOU CMP profile and drilling results obtained from Well Bogushevsk-2 reveals that the seismic sequence R_3^4or corresponds to the Riphean Belorussian Group and boundaries between its seismic members coincide with boundaries of the Rudnya and Orsha formations, which constitute the largest part of the cataplatform cover in the Orsha depression. For example, the boundary between the lower (R_3^{4-1}) and middle (R_3^{4-2}) seismic members is located in Well Bogushevsk-2 section at a depth of 1363 m; i.e., it corresponds to the boundary between the Rudnya and Orsha formations of the Belorussian Group (Fig. 2). Boundary between the middle (R_3^{4-2}) and upper (R_3^{4-3}) seismic members is located at a depth of 1070 m, where drilling recovered the lithologically specific upper subsequence of the Orsha Formation.

The **seismic member $\mathbf{R_3^{4\text{-}1}}$** is traceable through the Orsha depression, Usvyaty graben, and Velizh saddle. This seismic member is characterized by the fusiform section—it is truncated as toplap at the 105-km mark along the TVSB profile and pinches out as onlap near the 30-km mark in the ChOU profile (Fig. 2).

The seismic member corresponds to the Rudnya Formation up to 302 m thick, which rests usually upon the crystalline basement or the Sherovichi Group (only in Well Rudnyanskaya-1) and is overlain by the Orsha Formation or younger (Riphean Lapichi Formation or Vendian) rocks (*Geologiya* ..., 2001; Veretennikov et al., 2005).

The formation is subdivided into three members (Fig. 3) dominated by the fine-grained sandstones and the coarse-grained siltstones with intercalations of the medium- to fine-grained sandstones, clays, and clayey siltstones. Sandstones and siltstones are oligomictic and mesomictic (locally quartzose), usually slightly or moderately consolidated rocks with the clayey or dolomitic (in some sections and layers) cement. The rocks are mostly red-colored (spots, bands, and intercalations) and gray in the upper part. Most sections exhibit the rhythmical structure, intraformational hiatuses, intercalations, and clay balls (*Geologiya*..., 2001).

The **seismic member $\mathbf{R_3^{4\text{-}2}}$** is traceable along the entire ChOU profile with the increase of thickness and submergence of boundary surfaces toward the south. It is indistinguishable in the wavefield in the TVSB profile.

The seismic member corresponds to the mineralogically similar lower and middle subsequences of the Orsha Formation of the Belorussian Group (Fig. 3). It is composed of lihologically homogeneous, mostly red-colored quartzose sandstones with well-rounded and sorted grains. Their coarsest varieties are confined to the basal part of the formation. At the base (7–10 m), they grade frequently into gravel–pebble conglomerates with the basal coarse-grained cement. Gravel and pebbles are represented by vein quartz, quartzite–sandstones, and weathered igneous rocks (*Geologiya* ..., 2001).

The **seismic member $\mathbf{R_3^{4\text{-}3}}$** is similar to the underlying member in terms of its position in the section: it is

[1] Index or indicates belonging of the seismic sequence to the Orsha region.

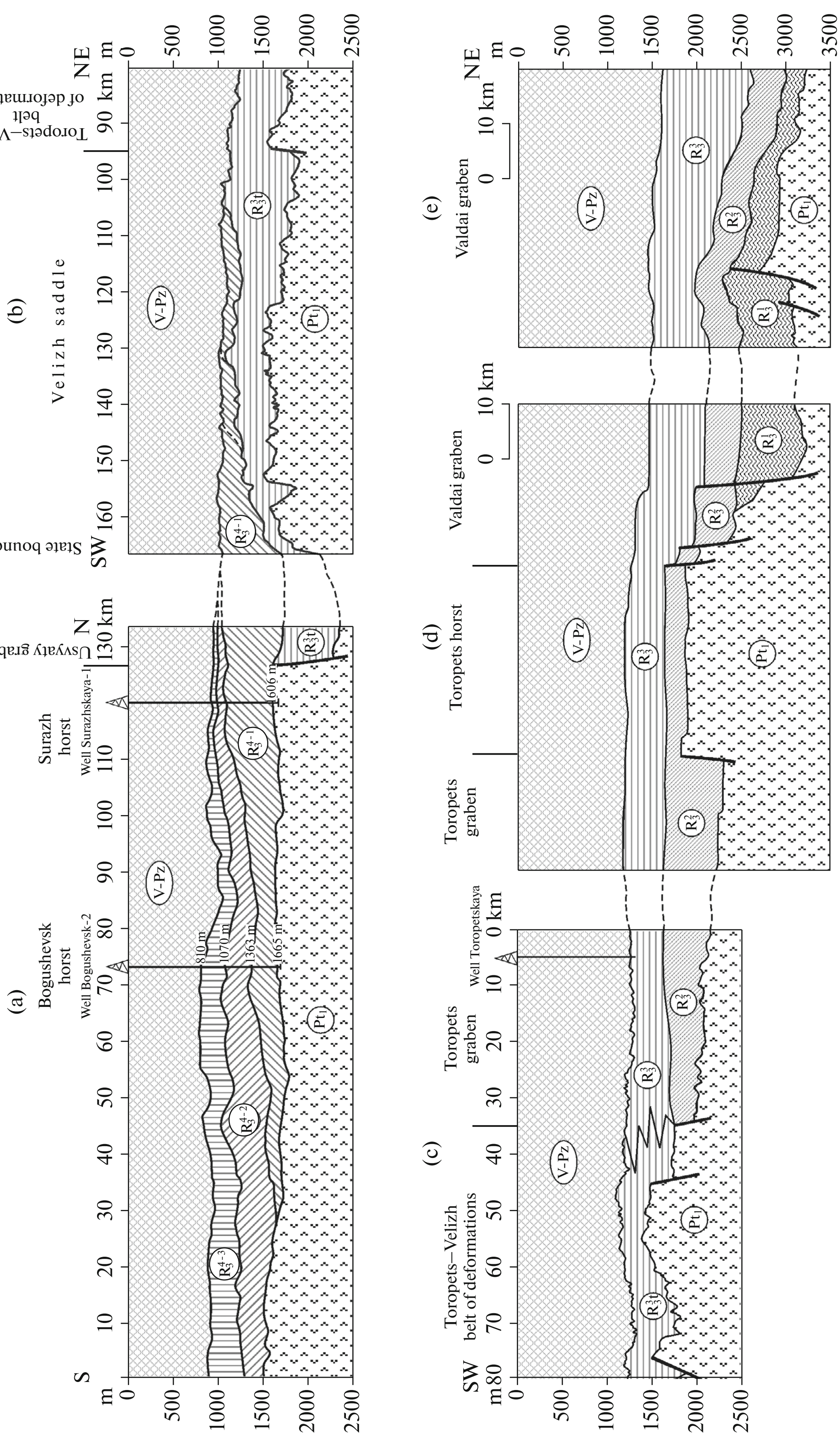

Fig. 2. Seismic–geological section along CMP profiles: (a) Cherikov–Orsha–Usvyaty (*Razlomy* ..., 2007; Chamov, 2016), (b, c) Toropets–Velizh state boundary (Kostychenko et al., 2008), (d) 09009-0900008-0900010, (e) Valdai–Demyansk–Nakhod (Kostychenko et al., 2008). For position of profiles, see Fig 1.

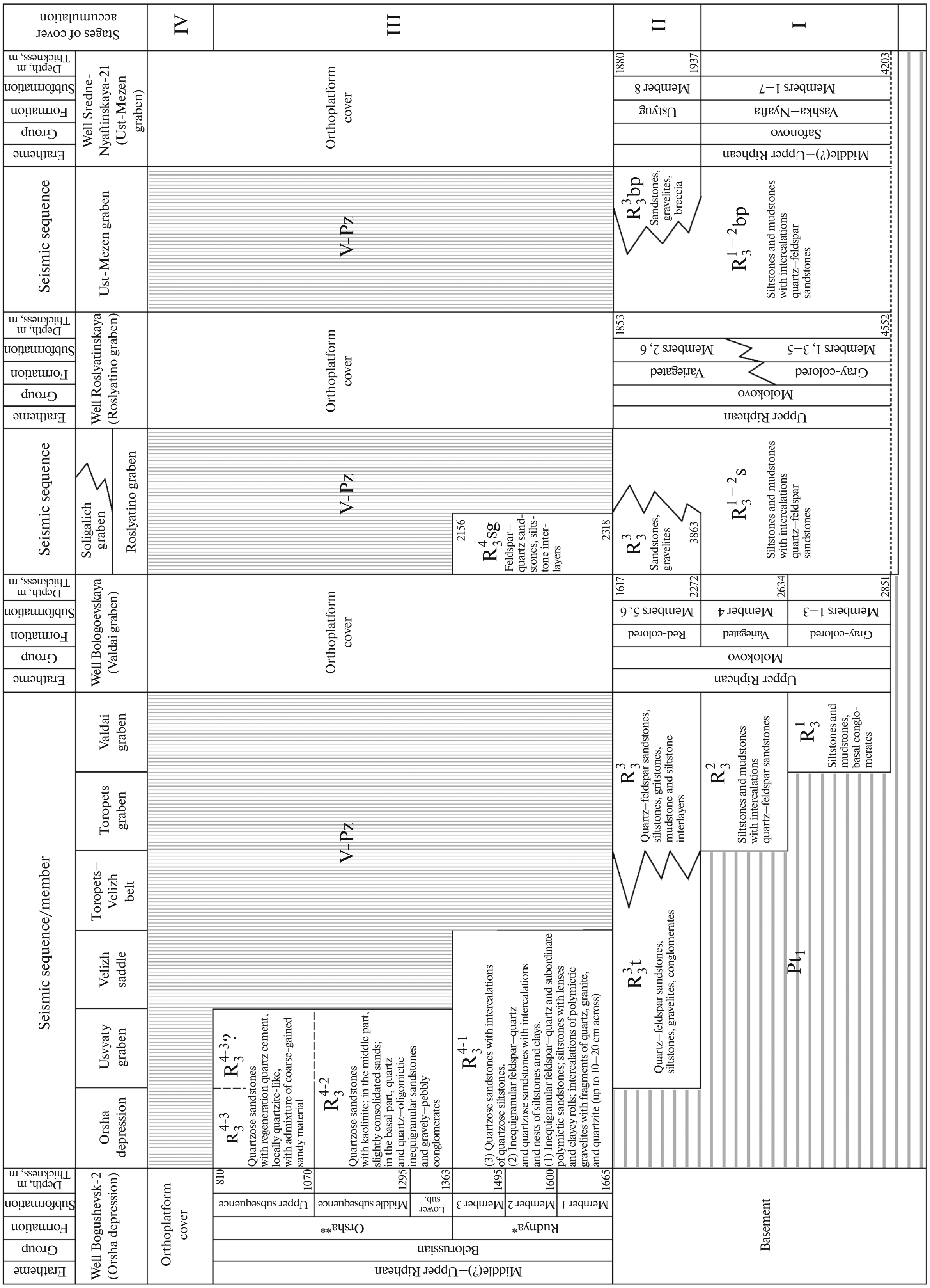

Fig. 3. Correlation between seismic sequences and stratigraphic units of the section. Drilling data from (Zolotov et al., 1971; *Geologiya* ..., 2001, Veretennikov et al., 2005; Aplonov et al., 2006; Chamov, 2016).
(I–IV) stages in accumulation of the sedimentary cover: (I–III) cataplatform: (I) main phase of graben formation, (II) terminal phase of graben formation—initial phase of postrift subsidence, (III) "protosyneclise", (IV) orthoplatform (syneclise).
For the position of wells, see Fig. 1.

also characterized by the increase of thickness and submergence of boundary surfaces toward the south. It is conceivable that the subsequence is truncated by rocks of the orthoplatform cover within the Surazh uplift and is missing above the Usvyaty graben.

This seismic member characterizes the lithologically specific upper subsequence of the Orsha Formation, which is dominated by quartzose sandstones with the regeneration quartz cement (Fig. 3).

The **seismic sequence $\mathbf{R_3^3t^2}$** occupies the lower structural position in the cataplatform cover in the region under consideration and rests upon the surface of the Lower Proterozoic crystalline basement. Depending on the spatial position in the Orsha–Central Russia transect, the seismic sequence is overlain by rocks of the ortho- or cataplatform cover (Fig. 2).

Along the TVSB profile, the maximum (400–600 m) and minimum (150–200 m) thicknesses of the sequence are observable in its northern and southern parts, respectively.

Toward the Orsha depression, the seismic sequence dips abruptly under rocks of the seismic sequence R_3^4 and is traced in Belarus (Fig. 2). At the northernmost flank of the ChOU profile between marks 126000 and 133000, the section demonstrates distinct stratification characteristic of sedimentary sequences rather than the chaotic wave record typical of metamorphosed rocks of the basement. The wavefield patterns allow an assumption that the Surazh basement inlier contacts in the north with the Usvyaty graben (named after the neighboring settlement), which is filled with stratified sedimentary sequences. The base of this graben is outlined at a depth of approximately 2300 m, i.e., substantially below the basement surface in the Orsha depression.

No structural boundaries of the seismic sequence R_3^3t or distinct changes in dynamic parameters of its reflections are observable in a northeasterly direction along the TVSB profile. This sequence is considered a structural and seismic facies analog of the seismic sequence R_3^3, which is recognizable along TVSB and VDN profiles (Fig. 3).

The **seismic sequence $\mathbf{R_3^3}$** is widespread in the southwestern part of the Central Russian aulacogen (Toropets, Ostashkovo, Valdai, and Molokovo grabens) and in adjacent areas. It is characterized by distinct intense (frequently discrete) reflections and sets of subhorizontal extended packets of reflections. Its boundary with the overlying Upper Vendian rocks is readily recognizable owing to distinctly curved packets of reflections, which pinch out under the Upper Vendian seismic sequence.

[2] Index t indicates belonging of the seismic sequence to transitional areas between the Orsha and Central Russian regions.

Thickness of this seismic sequence decreases from 1000 to 250 m toward the adjacent areas. Despite this fact, the sequence is most widespread precisely in its southwestern part, where it overlies significant areas of the seismic sequences R_3^2 and R_3^1 and basement uplifts; i.e., this sequence "splashes" over slopes of aulacogen grabens (Fig. 2).

The seismic sequence in question corresponds to the upper red-colored part of the Molokovo Group, which is definable based on drilling data from the parametric Well Severo-Molokovskaya in the Central Russian aulacogen (Chamov et al., 2010; Chamov, 2016).

The sequence is largely composed of the coarse-grained poorly sorted arkosic sandstones compositionally uniform in all facies types of both red- and gray-colored rocks, which implies a stable source of detrital material. Sandstones are oligomictic and arkosic feldspar–quartz rocks with the gravel-sized fragments of gneissose crystalline rocks from the basement. Clastic material is usually poorly rounded. The general textural–lithological immaturity of sediments indicates proximity of the clastic material source. Rock-forming clastogenic minerals are dominated by the cataclased quartz derived from the granite–gneiss rocks, which are widespread in the basement of the Central Russian aulacogen.

The **seismic sequence $\mathbf{R_3^2}$** exhibits diverse type of reflections in different parts of the section, which is explained by its heterogeneous lithology.

In the southwestern part of the aulacogen, this seismic sequence is confined to the middle part of the cataplatform cover like the corresponding variegated part of the Molokovo Group (Fig. 3). In its distribution area, the sequence is sandwiched between the seismic sequences R_3^1 and R_3^3. In the Toropets graben, it is located at the base of the cover and is missing in the adjacent areas (Fig. 2).

Thickness of this seismic sequence varies from 450 to 600 m.

The **seismic sequence $\mathbf{R_3^1}$** is characterized by distinct boundaries and extended well-stratified internal reflectors. It occupies the lower structural position and is traceable over a smaller area as compared with the overlying seismic sequences of the Molokovo Group. The sequence is readily distinguishable at the base of sedimentary sections of most grabens in the southwestern part of the aulacogen. However, it is missing from the cataplatform sedimentary cover in the Toropets graben and southern area.

The features described above indicate the lacustrine nature of sediments in the gray- and red-colored sequences of the Molokovo Group. Their facies composition reflects differences in the hydrodynamics of depositional environments. Thin well-stratified sediments of the gray-colored sequence are characteristic of the calm setting of relatively deep lakes, while more sandy and less sorted red-colored sediments accumulated in relatively shallow-water depositional environments.

The feature in common for these sediments is the structural control of their lateral distribution, while the depth of graben determined the facies appearance of rocks as well. Bedding patterns in the section of the Molokovo Group reflect the influence of relatively intense bottom and/or alongshore currents, as suggested by the wide development of wavy and small-scale cross bedding. The wide development of slump structures indicates the deposition of sediments on steep slopes, which is well consistent with the tectonic bounding of the basin. Frequent distortions of bedding (overturned position of parallel-bedded sediments and microfaults in sediments) reflect tectonic mobility of the graben bottom. The frequent occurrence of typically terrestrial variegated intercalations enriched with ferruginous matter can also be explained by variations in the tectono-depositional setting. The composition of organic remains from the gray-colored sediments of the Molokovo Group is also indicative of lacustrine sedimentation. The scarcity of microfossil assemblages and their distinct difference from the typical Riphean assemblages of continental seas can indicate "stress" conditions typical of lacustrine settings owing to frequent variations in the subsidence rate and, correspondingly, depth of the basin and the degree of its compensation by sediments.

The **seismic sequence $R_3^{1\text{-}2}s$**[3] characterizes the northeastern part of the Central Russian aulacogen, where the sedimentary section differs appreciably from the southwestern flank (Fig. 3). Thickness of this seismic sequence varies from a few hundreds of meters to 2 km.

The available seismic data provide no grounds for reliable tracing of the seismic sequence R_3^1 at the northeastern flank of the aulacogen. At the same time, on the basis of similarity in the facies, mineralogical, and petrophysical properties of gray-colored rocks recovered by Wells Roslyatinskaya, Bobrovskaya, and Velikoustyugskaya, it is assumed that this seismic sequence constitutes the main part of the preplate sedimentary cover at the northeastern flank of the aulacogen.

In addition, the structural position and seismostratigraphic significance of the seismic sequence R_3^2 changes as well. In the southwestern part of the Central Russian aulacogen, this seismic sequence corresponding to variegated rocks of the Molokovo Group occupies an intermediate position along both vertical and lateral directions. This fact served as a basis for its recognition as an autonomous stratigraphic unit. In the northeastern part of the aulacogen, the situation is different: the seismic sequence R_3^2 disappears as an autonomous stratigraphic unit, but it is repeatedly noted in the section as a facies indicator of the shoaling of relatively deep lakes. These facies features are confirmed by the data from Well Roslyatinskaya, one of the deepest wells drilled in the aulacogen. The well recovered alternating gray-colored (members 1 and 3–5) and variegated (members 2 and 6) sediments (Fig. 3).

The seismic exploration data provide no grounds for establishing seismofacies elements of the section, which could be correlated with the seismic sequence R_3^3 typical of the southwestern flank of the aulacogen. Correspondingly, no regular increase in the distribution area of red-colored sediments in the cataplatform cover, which is typical of the whole northeastern part of the aulacogen, is documented for its southwestern flank. Nevertheless, sediments of the red-colored sequence are known in the northeastern part of the aulacogen in the Soligalich area. The section recovered by Well Soligalichskaya is largely composed of the coarse-detrital psammitic rocks, which are divisible into three members (Zolotov et al., 1971)

Red-colored coarse-grained arkosic sandstones, gravelites, and breccia of the lower member recovered in the depth interval of 2925–3863 m are best consistent by their facies appearance and mineralogical–petrographic composition with the red-colored sequence of the Molokovo Group. Red-colored and variegated mica–quartz–feldspar sandstones of the middle member (2318–2925 m), which contains a mineral assemblage of the heavy fraction characteristic of all sequences of the Molokovo Group, belong likely to the same seismic sequence (Fig. 3).

The upper member of rocks recovered by drilling in the interval of 2156–2318 m defined as the Obnora Formation in (Kirsanov, 1968) is represented by the pinkish brown fine- to medium-grained feldspar–quartz sandstones with thin siltstone intercalations. Minerals of the heavy fraction in these rocks are dominated by garnet.

The sharp difference between compositions of the heavy fraction from this member and Molokovo Group indicates the appearance of a new source of clastic material for the aulacogen. It should be noted that garnet is a typomorphic mineral for the Vendian section (Ozhiganova, 1960; Lagutenkova and Chepikova, 1982; Kozlov et al., 1995). Its dominant role in the heavy fraction suggests the Vendian age of sediments from this interval. Judging from the structural position and mineral composition, which differs from that in the underlying sequences, they are the youngest sediments of the cataplatform development stage and are conditionally attributed to the seismic sequence R_3^4sg (index sg indicates its development in the Soligalich area).).

[3] Index s indicates belonging of the seismic sequence to the Central Russian aulacogen.

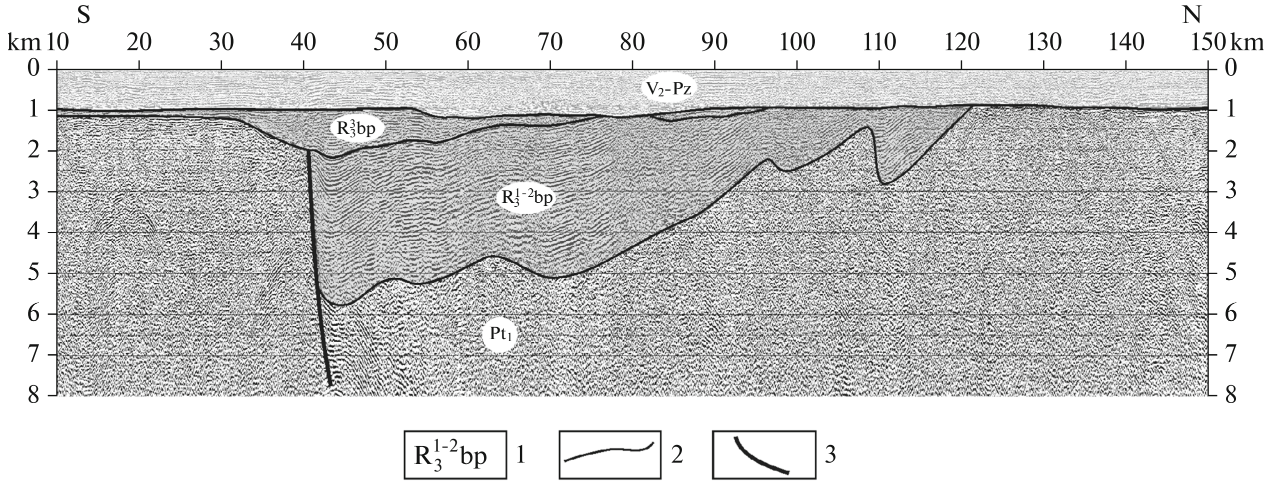

Fig. 4. Seismic—geological section of the Severnaya Dvina graben along the profile I fragment.
(1) Seismic sequences; (2) boundaries of seismic sequences; (3) fault.
For the position of grabens and profile, see Fig. 1.

The **seismic sequence** $\mathbf{R_3^{1-2}bp}$[4] unites all the seismostratigraphic units filling the White Sea—Pinega grabens. It rests upon the basement with the uppermost part being truncated by the sedimentary complex of the orthoplatform cover or overlain in form of the toplap unconformity by sediments of the higher seismic sequence R_3^3bp.

In seismic records, dynamically distinct horizons are characterized by the fan-shaped structure in sections orthogonal to the strike of half-grabens or by irregular wavy bedding in sections subparallel to long axes of these structures (Fig. 4).

Sharp asymmetry in the structure of most grabens results in significant variations in the thickness of this sequence. For example, they may be as thick as 5—7 km near steep slopes of half-grabens (near surfaces of fault planes), but pinch out across the strike of the structure at a distance of 10—15 km.

By its structural position, facies composition, and variations in the thickness of sediments, the seismic sequence R_3^{1-2}bp represents an analog of the seismic complex R_3^{1-2}s defined in the northeastern part of the Central Russian aulacogen (Fig. 3). The available data support the idea of tectono-depositional similarity between sections of the Central Russian and White Sea—Pinega regions. Although the names of formations accepted in these two regions are absolutely different, their sections are quite comparable and may be described, for example, in terms of the Molokovo Group, where different combinations of sequences characterize exhaustively the cataplatorm cover of both regions.

The Ust-Mezen graben is now best studied by seismic exploration and drilling (Fig. 1). Like the Kerets, Kepin, and Leshukon grabens, it is confined to the widest part of the Terskii—Pinega branch of the basin (Fig. 1). In the section of seismic profile I, these structures look like unipolar asymmetrical half-grabens, which are formed on account of normal faults dipping in the southwestern direction. Seismic sequence R_3^{1-2}s includes several seismic facies, which may be correlated with local stratigraphic units (formations) defined in Well Sredne-Nyaftinskaya-21 section drilled on the eastern slope of the Ust-Mezen graben.

The section of this part of the cataplatform cover is divided into five formations[5]. The *Nyafta Formation* (depth 1937—2134 m, thickness 197 m) was likely formed on the coast of a large lake. For example, the varved patterns of sediments combined with slump structures, bedding distortions and structures in the form of hummocky oblique bedding (influence of storm waves) represent features indicating the deposition in shallow mobile settings. The diverse and abundant assemblage of organic remains and gray color of sediments imply relatively deep depositional environments. The presence of silty material in marlstones and fine-grained limestones is determined by the close position of the shore.

The Nyafta Formation in the reference section of Well Sredne-Nyaftinskaya-21 is correlated with the Chapoma Formation, Upper Riphean sediments of which were recovered in the Chapoma River valley on the Terskii coast of the Kola Peninsula (Baluev et al., 2010). Rocks of this formation are present in the axial part and along the northeastern slope of the Chapoma

[4] Index bp indicates belonging of the seismic sequence to the White Sea—Pinega region.

[5] Detailed description of rocks constituting the reference section is given in (Chamov, 2016).

graben (Fig. 1), where the terrigenous sequence is largely composed of variegated silty and clayey rocks with the chlorite–carbonate cement. In the upper part of the section, clayey siltstones are intercalated by dark gray to black carbonate siltstones alternating with clayey dolomites. The rocks exhibit ripple marks and abundant desiccation cracks indicating multiple, evidently brief, desiccation of the basin.

The *Leshukon Formation* (depth 2134–2530, thickness 396 m) is characterized by the high content of sandy material, regressive–cyclic structure of the section, development of slump structures of variable orders, and presence of flow structures (cross bedding and sandy lenses), which imply the unstable intermittently changeable hydrodynamic regime: alternation of flooding and shoaling periods. Such conditions could appear owing to changes in the hypsometric position and inclination of the basin bottom during the formation of grabens (small tucked blocks, appearance/disappearance of flows along transfer zones, and others). Variegated coloration of sediments in the lower part reflects the influence of subaerial areas of detrital material mobilization.

The *Dorogor Formation* (depth 2530–3090 m, thickness 560 m) is largely characterized by the coarse-grained composition of sediments. Combined with the variegated coloration, wide development of hiatuses, and absence of fossils, this composition indicates terrestrial depositional environments with the periodic influence of intermittent flows. High activity of these flows is evident from the presence of erosional pockets filled with clayey material.

The *Peza Formation* (depth 3090–3647 m, thickness 557 m) is characterized by the rhythmical structure of the section. The presence of transgressive–regressive successions, general gray coloration of sediments, and relatively abundant organic remains indicate repeated flooding with the subsequent shoaling of the sedimentation basin, while the occurrence of gradational and cross-bedded gravelites and clayey rolls at the base of cycles implies fluvial–proluvial depositional environments at early stages of the bottom subsidence. When the sedimentation basin was closed, it accumulated regressive successions characteristic of lacustrine sedimentation. The subsequent tectonic movements (normal faults) destroyed for some period a sluice to form a new sedimentation basin, which, in turn, determined the onset of a new transgressive cycle.

The *Vashka Formation* (depth interval 3647–4203 m, thickness 556 m) is subdivided into three autonomous sequences, which reflect depositional settings characteristic of overlying sedimentary complexes. The presence of cross bedding and clayey rolls in sandy and gravelly sediments suggests the periodic influence of fluviatile flows. Lacustrine settings are reflected in the appearance of wavy and parallel bedding, gentle asymmetrical unidirectional current ripple marks and subsymmetrical wave ripple marks of the opposite direction in siltstones. Moreover, even the finest and presumably deepwater varieties of sedimentary rocks (parallel-bedded carbonates, siltstones, and dark gray mudstones) enclose intercalations with thin- to medium- cross bedding, erosional incisions, and desiccation cracks. The presence of cracks indicates unambiguously the aerial position of watered sediments. The development of large (2 to 3 m) transgressive gravelite–sandstone–siltstone rhythms is consistent with the assumption of periodic sedimentation in the barrier basin. Distinct variegated coloration of basal sediments resembles lacustrine sections of the Central Russian aulacogen such as, for example, facies of fault-line depressions.

Analysis of the mineralogical–petrographic composition recovered by the parametric Well Sredne-Nyaftinskaya allows the conclusion that the cataplatform cover is characterized by the two-stage mineralogical structure. The lower stage, which includes the Vashka and Peza formations, is represented by the polymictic terrigenous mineral association with the content of quartz grains amounting to 40–50%. The upper stage, which unites the Dorogor, Leshukon, Nyafta, and Uftyug formations, is characterized by the oligomictic terrigenous mineral association with a high content of quartz (70–80%).

The **seismic sequence $\mathbf{R_3^3bp}$** forms series of intense extended continuous, relatively gentle, syncline-shaped reflections resting with angular unconformity upon the underlying seismic sequence R_3^{1-2}bp and overlies (completely or partly) shoulders of downdip blocks and inliers of the basement. For example, in the Severnaya Dvina graben section belonging to the Kandalaksha–Severnaya Dvina branch of troughs, the seismic sequence R_3^{1-2}bp is represented by a package of thin gentle lenticular–bedded reflections in the profile interval of 30–75 km and probably 83–95 km, which rest with a notable angular unconformity upon inclined reflections of the underlying sequence, truncate them, or "splash" over the southwestern slope of the graben (Fig. 4).

By its structural position, the seismic sequence R_3^3bp is an analog of the seismic sequence R_3^3, which occupies the upper structural position in the cataplatform cover of the Central Russian aulacogen (Fig. 3). The seismic sequence is not pervasive. Its thickness is highly variable (difference up to 1000 km) averaging a few hundreds of meters.

By its structural position and facies composition of sediments in the section of the Ust-Mezen graben, the seismic sequence R_3^3bp is best correlative with the Uftyug Formation (Fig. 3). Red-colored and variegated sediments of the formation recovered by Well Sredne-Nyaftinskaya in the depth interval of 1880–1937 m are largely sandy in composition. They are characterized by large-scale unidirectional cross bedding, distinct features indicating the aerial sedimentation setting (rock varnish[6]), and lack of fossils. Such facies features reflect the unstable fluvial–proluvial depositional environment characteristic, for example, of continental valleys along faults scarps. The presence of peculiar "intraformation breccia" indicates tectonic activity in the sedimentation basin.

DISCUSSION

Position of Seismic Sequences in the Section and Stages of the Cataplatform Cover Formation in the Province

The structure and position of seismic sequences in the Province demonstrate several regularities in common, primarily their rejuvenation and hypsometric rise in the southwesterly direction from the White Sea–Pinega region toward the Orsha region (Figs. 2, 3). In this direction, the pelite and fine-detrital gray-colored sediments are gradually replaced by the psammitic and psephitic red-colored varieties. Changes in the facies setting are accompanied by changes in the mineral composition: typical arkosic rocks in northeastern parts of the section give place to oligomictic and quartz terrigenous-mineral associations.

Some maturation of mineral associations without principle changes in the clastic source may be related to peculiarities in development of the strike-slip–normal fault system. For example, the structure of conjugate half-graben characteristic of the White Sea–Pinega grabens may be characterized as a system of "domino" extension. In these structures the sediment accommodation space is not directly proportional with the extension value, and the influx of sedimentary material is determined by rise/subsidence patterns of individual parts of rotated blocks (Allen and Allen, 1990).

The formation of such tectono-depositional systems stimulates the intensification of sediment reworking during the tectonic development of structure. The most intense formation of the sediment accommodation space is characteristic of the initial extension stage, which results in the accumulation of less mature sediments. The further evolution of the structure is accompanied mostly by the redistribution of this available accommodation space, which stimulates, in turn, intraformation redeposition (recycling) of clastic material, not the influx of its new portions. The influence of out-of-basin sources decreases gradually down to the zero influx of clastic material from outside and the formation of sandy rocks exclusively on account of the reworking of accumulated sediments. It is conceivable that the higher maturity of rocks from the upper stage of the Riphean section is explained precisely by these processes.

[6] Films of rock varnish were formed at the initial stage of sediment transformation. Subsequently, ferruginous films were overlain by the regeneration quartz cement.

The structure of seismic sequences and relations between them, as well as the composition and facies appearance of lithological varieties, characterize stages in the tectono-depositional development of the Province. Three stages are readily definable in the formation of the cataplatform cover (from the base upward) (Fig. 3):

(1) main phase of the graben formation (seismic sequences R_3^{1-2}s and R_3^{1-2}bp in the Central Russian and White Sea–Pinega regions);

(2) terminal stage in the graben formation—initial stage of postrift subsidence (seismic sequences R_3^3t, R_3^3, and R_3^3bp in all regions of the Province); and

(3) formation of the non-riftogenic Orsha depression (protosyneclise) (seismic sequence R_3^4 in the Orsha region).

These different (in duration and pattern) stages reflect the evolution and trend of tectono-depositional processes at the transition between the cata- and orthoplatform regimes in development of the East European Platform.

Differences in the structure of the cataplatform megacomplex of the Central Russian–Belomorian province reflect different histories of the tectonic and depositional development of several key structures, which are considered below.

The Central Russian and White Sea–Pinega Regions

The available structural, lithofacies, and seismostratigrahic data support the concept of genetic relationship of the Central Russian and White Sea–Pinega regions. Cataplatform tectono-depositional systems of these regions were previously considered geodynamically conjugate elements of the craton: Central Russian–Belomorian tectonic pair (Chamov, 2016).

In both regions, large-scale strike-slip movements resulted in the formation of complex lithotectonic ensembles, where conjugate half-grabens form transitional structures of the pull-apart type (Fig. 2).

Local tectonic processes proceeding against the background of the general geodynamic regime determine peculiarities of individual grabens. For example, the structure of local grabens is determined by the relationship between the planes of Neoproterozoic faults and the inclination of Paleoproterozoic blastomilonite slices that take part in the basement structure (Chamov, 2015).

If normal faults crossed the gently inclined blastomilonite beds, grabens with the rheologically determined subsidence limit (Molokovo type) were formed. In such a situation, the subsidence of granite rocks into the denser amphibolite substrate was constrained by isostatic leveling forces. If the regional strain field remained stable after reaching the subsidence limit, such grabens experienced lateral extension, which resulted in the accumulation of regressive sedimentary successions with irreversible transition from the lacustrine to fluvial–proluvial facies. Precisely such dynamics in the basin development is reflected by the regressive succession of seismic sequences R_3^1–R_3^3 in the southwestern part of the Central Russian aulacogen.

The more advantageous (with respect to energy) development of normal faults along steeply dipping blastomilonite beds (Roslyatino type) did not disturb the isostatic equilibrium and promoted the formation of narrow deep grabens, where deposition environments remained virtually unchanged with time. Such a style of tectonic development in both regions is evident from the structural features of the seismic sequences R_3^{1-2}s and R_3^{1-2}bp.

The peculiar fan-shaped structure of seismic sequences, which is determined by the structural asymmetry of half-grabens, also reflects regularities in the accumulation of sedimentary complexes. The presence of numerous unconformities in them indicates the multistage subsidence history of half-grabens with the successive and geologically instant (fault-induced) formation of a new sedimentation basin. The tectonic event preceding sedimentation is reflected in the peculiar onlap of reflectors: after the regular formation of normal faults, sedimentary layers accumulated there pinch out near the inclined surface of the previous sedimentary series.

The seismic facies analysis reveals the high facies variability of sedimentary complexes (formations). Elements of seismic successions demonstrate different structures, which indicate changes in the depositional environment.

Regressive successions typical of sedimentation in temporary lakes are widespread (from the base upward): the packet of extended fan-shaped reflections is replaced by members with short discrete and, further, chaotic patterns of the wavefield. Discrete reflections with a variable intensity imply unstable hydrodynamic depositional settings that are characteristic of fluvial sediments.

The above-mentioned reflection types are widespread and observed alternating with each other at different levels of the section. Hence, deposition of the cataplatform cover took place under different dynamic conditions and repeated changes from the subaqeous to subaerial setting. All sedimentation settings considered above could be developed in the lacustrine and valley landscapes formed along scarps of normal faults.

The Orsha Region

The structure of the depression in the crystalline basement relief is discussed in detail in (Aizberg et al., 1985, 2004; Kudryavets et al., 2003; *Razlomy* ..., 2007). Many researchers attribute the Orsha depression to the Volyn–Orsha paleotrough representing an early paleorift of the East European Craton (Aizberg et al., 2010). The paleotrough is considered a southwestern continuation of the Central Russian aulacogen in the form of single Volyn–Central Russian lineament of the Riphean age (Aizberg et al., 1985, 2010; Nagornyi, 1990; Garetskii, 1995; *Razlomy* ..., 2007; and others). Such concepts are contradictory.

The Orsha depression differs from other tectono-depositional systems of the Province by several parameters such as the structure (flat-bottom depression without distinct tectonic boundaries versus fault-line grabens), wavefield patterns (undoforms versus graben successions), unidirectional transport of clastics (from the north southward), composition of sedimentary rocks (quartzose versus arkosic), and depositional settings (coastal marine versus terrestrial). In addition, the established onlap relations of the Belorussian Group sequences (seismic sequence R_3^4) with the uppermost layers of the seismic facies analog of the Molokovo Group (seismic sequence R_3^3t) indicates a later formation of the structure and sedimentary infill of the Orsha depression as compared with the Central Russian aulacogen. It means that the Central Russian aulacogen and Orsha depression have never been elements of a single geodynamic system because of different ages and formation conditions.

Analysis of seismic exploration and drilling data allows us to reconstruct the probable tectono-depositional history of initiation and development of the Orsha depression. The seismic sequence R_3^3t, which is partly located in the Usvyaty graben, distorts the above-described regularity in the position of seismic sequences in the cataplatform cover section of the Province. It is located lower as compared with its seismic facies analogs in transboundary areas and the Orsha depression basement.

The seismic profile ChOU demonstrates that subsidence of this fragment of the seismic sequence is related to normal faults in the basement and occurred after the accumulation of red-colored psephitic sequences (Fig. 2). It is logical to assume that movements along normal faults were determined by the regional structural reorganization, which resulted in initiation of the Orsha depression in the southwestern part of the Province.

The absence of any features indicating pinching out of the seismic sequence and, in contrast, the presence of distinct structural (fault) boundaries implies tectonically instant (catastrophic, fault-induced) selective subsidence of the cover fragment. This saved the fragment from erosion unlike other fragments of the seismic sequence that avoided faulting.

Such conditions could result from the combination of subsidence and simultaneous "squeezing out" of some blocks with the selective preservation of subsided fragments and intense erosion of others. In this respect, rocks of the seismic sequence R_3^3t in the Usvyaty graben can be considered relicts of some pre-Orsha sedimentary basin. Similar situation was likely characteristic of the Gatyn Formation of the Sherovichi Group, a litholofacies analog of red-colored psephites of the seismic sequence R_3^3t, which constitutes the lower structural stage of the cataplatform cover (Makhnach et al., 1979). For example, according to (Aizberg and Starchik, 2013), the relatively deep pra-Orsha depression, which likely represented the southern centriclinal closure of the Central Russian aulacogen, i.e., developed as a rift structure, was formed during the Sherovichi time. Such a point of view seems quite logical since the spatially isolated fragments of grabens filled with red-colored arkoses were recovered by some wells in spatially limited areas and are not correlated with other elements of the cover by seismic exploration profiles.

Let us imagine processes, which took place at the initial stage of the Orsha depression formation and resulted in the faulting and subsidence of a fragment of the seismic sequence R_3^3t in the Usvyaty graben.

At first sight, it would be more logical to explain the formation of the Orsha depression by secondary (relative to the horizontal strike-slip) descending movements since the postrift subsidence is widespread in all the extension systems. Owing to its structural position between sedimentary complexes of the Central Russian aulacogen and platform cover, the depression proper could be considered a protosyneclise, initiation of which triggered general downwarping of the Province with progradation of Vendian rocks in the northeasterly direction. At the same time, the location of the Orsha depression in the area with an unthinned crust and away from riftogenic structures casts doubts on the hypothesis of its postrift subsidence.

It seems that these processes are related to some other mechanism, which may be understood from the analysis of the regional structure. The latter experienced no principle changes since the Orsha depression formation at the end of the cataplatform stage because of burial under rocks of the orthoplatform cover.

The Orsha depression is confined to the Novgorod syntaxis, which represents a complex conjunction area of basement lineaments and Neoproterozoic tectono-depositional systems. In this area, several large basement elements of variable age, strike, and tectonic nature are sharply curved and strive to a single center, which is located south of the Novgorod massif salient (Fig. 5).

The structure of the basement in the southwestern segment of the Province is best evident from sharp virgations of axes of magnetic anomalies. A.D. Arkhangel'sky was the first to note this feature in the 1940s, which is reflected in most tectonic maps. Views on the structure under consideration are very ambiguous. For example, this area was considered reflection of the Upper Volga mantle plume (Orovetskii, 1990), the continental breakup center (Zonenshain et al., 1990), the upper Volga spiral structure hosting grabens and aulacogens at the periphery (Nagornyi, 1990), or Slobodskoi tectono-geodynamic juncture related to descending convective movements in the mantle (Garetskii et al., 2007; Garetskii and Karataev, 2009, 2014).

In my opinion, the convergence of structures could occur as a result of lateral compression (pinching) of the Central Russian–Belomorian belt and its potential continuation in the westerly direction: sublatitudinal system of fractures with features of strike-slip displacements (Chamov, 2016). The latter system was outlined by the gravity and magnetic data as a series of sublatitudinal fractures accompanying the superregional preplate Polotsk fault defined by R.G. Garetskii in 1974 and named as the Polotsk–Kurzem (Karataev and Pashkevich, 1985) or Kaunas–Polotsk (Mastyulin et al., 1991) system. The subsequent data made it possible to speak about the relatively wide Polotsk–Kurzem extension structure, which was formed simultaneously with the whole system of Riphean rift structures in the East European Platform (Garetskii et al., 2002, 2004; *Razlomy* ..., 2007). This composite and extended arcuate belt coincides mostly with the Lapland–Central Russian–South Baltic belt defined by M.V. Mints with colleagues (*Glubinnoe* ..., 2010).

The domain "squeezed" between the salient of large elements of the basement represents a central element of the syntaxis. Following (Garetskii et al., 2007), it is termed here as the Slobodskoi juncture. In this area, the basement is represented by a mosaic of blocks (Nevel, Lepel, and others) with features of tectonic deformation (*Razlomy* ..., 2007). The vertical gradient of the anomalous magnetic field demonstrates many short and chaotically arranged axes of magnetic anomalies, which reflect a complete reworking of rocks by tectonic movements (Chamov, 2016).

The age of the Novgorod syntaxis remains unclear. However, initiation of the Upper Vendian Redkino sequence (approximately 600 Ma ago), which overlies structures of the preplate tectonic stage, can be considered the upper (youngest) age limit of its formation.

The syntaxis could be formed at the end of the cataplatform stage owing to the displacement of one (primarily, Voronezh) or several large blocks of the basement (indenters) in the northerly and northwesterly directions toward the Novgorod massif (ramp) (Fig. 5). Such an assumption is supported by the data on intense deformation of small bocks of the basement immediately in the Slobodskoi juncture, a potential area of squeezing out and hummocking, in addition to the general structural situation (*Razlomy* ..., 2007).

Collisions are responsible for the formation of structures of lateral squeezing out, which is evident in different tectonic domains (Kopp, 1997). One of the most important consequences of such processes is

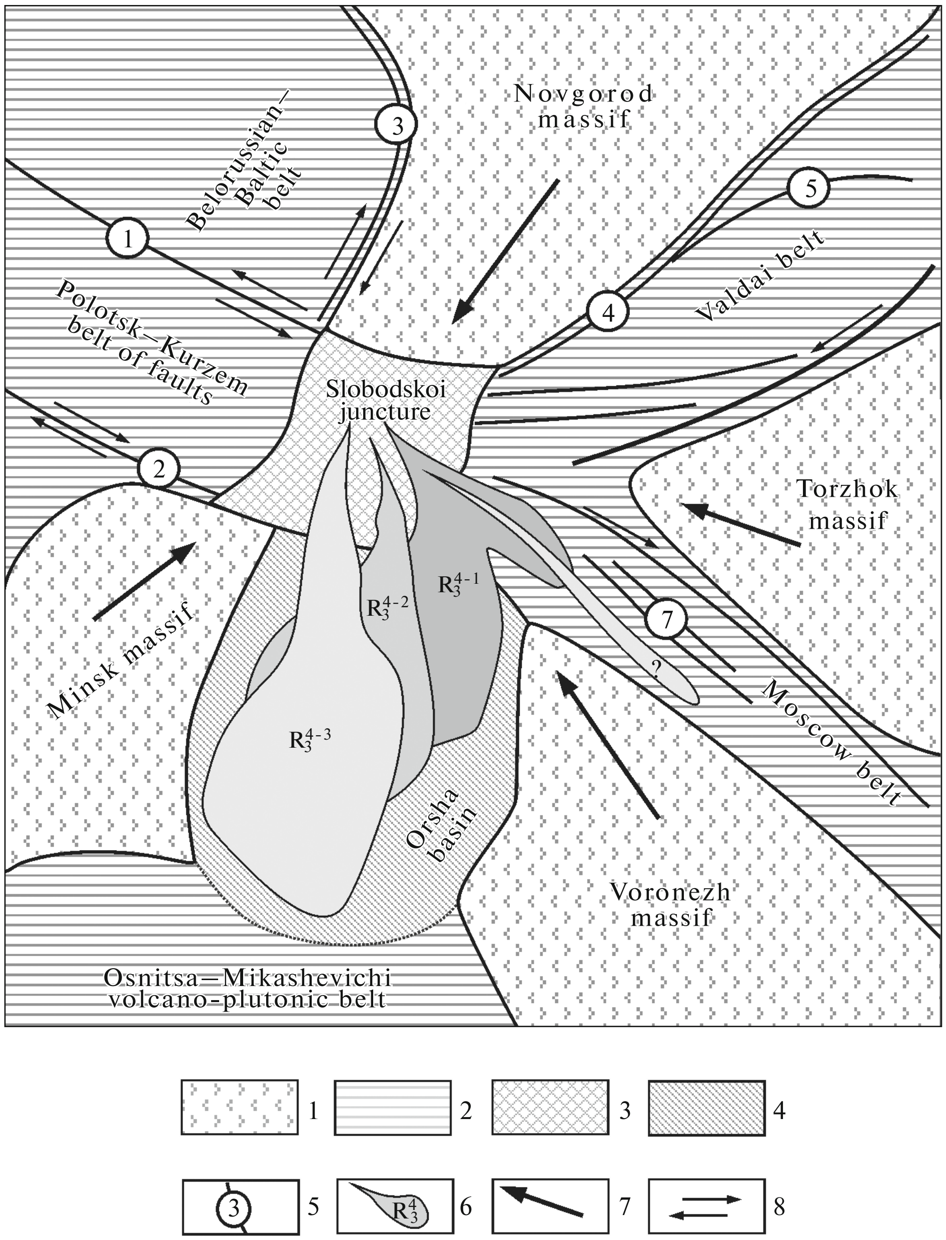

Fig. 5. Structure of the Novgorod syntaxis and tectono-depositional model of the Orsha depression development.
(1–4) Structural elements of the syntaxis: (1) indenters/ramps, (2) mobile belts, (3) area of vertical material squeezing-out, (4) Orsha compensatory depression; (5) faults: (1) Liepaya–Loknov, (2) Neman–Polotsk, (3) Pskov, (4) Lovat, (5) Kholmsk–Borovichi, (6) Bologoev, (7) Bel'sk; (6) flows of clastic material (seismic sequence R_3^4); (7) vectors of maximum stress; (8) strike-slip faults.

exhumation of huge volumes of the tectonically mobilized (crushed, disrupted, and so on) material into the erosion zone with the simultaneous appearance of sediment accommodation spaces (structural traps), which compensate compression and are filled with clastics transported from the syntaxis. The compensatory basin formed in this process is characterized by ordinary (not tectonic) boundaries and flat bottom complicated by fan-shaped folds gradually widening away from the syntaxis. With the formation of a new sediment accommodation space, the latter becomes filled by detrital material transported from the area of vertical "squeezing out" (Kopp, 1997).

All the above-mentioned features of the compensatory basin are reflected in full measure by the bottom structure and sedimentary complexes. The increment of clinoform progradational sedimentary bodies in the N–S direction, which is reliably established on the basis of seismic exploration data, indicates the presence of a source of abundant clastics in the assumed maximum compression area (Slobodskoi juncture). Proceeding from the aforesaid, the Orsha depression can be considered a compensatory basin adjacent to a lateral pinch of the sublatitudinal belt (Fig. 5).

The peculiar quartzose composition of sediments is characteristic only for the depression. Special investigations (Kostyleva and Simanovich, 2007) demonstrate its uniqueness and inconsistency with rocks surrounding the depression. This means that the specific clastic material was supplied by a source that existed in the erosion zone during the depression filling by sedimentary material. The nature of this specific source of quartz remains unclear. Inasmuch as it is considered the hydrothermal one (Kostyleva and Simanovich, 2007), it is logical to assume that the influx of siliceous material was related to the discharge of hydrothermal fluids in the area with intense destruction of the consolidated crust.

It is traditionally believed that the accumulation (maturation) of quartzose sequences requires much time[7]. At the same time, if the skeletal framework of these sandstones is thoroughly investigated, it appears that their mineralogical maturity is significantly overestimated. First, they demonstrate increase of the quartz component upward the section from the polymictic–oligomictic association to the appearance of quartzose sandstones in the upper subsequence of the Orsha Formation, which reflects the increasing influence of the specific source. Second, sandstones are absolutely unsorted and contain clayey rolls and secondary cement. In addition, the time of the Orsha depression formation is limited by the accumulation period of Upper Riphean rocks of the seismic complex R_3^3t and Upper Vendian orthoplatform cover.

Thus, the directed change of terrigenous–mineral associations from the quartz–feldspar association to the exclusively quartzose one due to long-term development of the structure and intrabasin reworking of material seems unlikely.

CONCLUSIONS

The main results of this work are as follows.

(1) The combined analysis of seismic and drilling data reveals that seismic sequences defined on the basis of their distribution areas, inclination, and dynamic intensity of the bounding and internal reflections are consistent with lithostratigraphic units of the section based on drilling results and can be used for mapping geological bodies within the cataplatform cover.

(2) The structure and position of all seismic sequences of the Province exhibit some regularities in common: primarily, rejuvenation and hypsometric rise in the southwesterly direction from the White Sea–Pinega region toward the Orsha depression. The gradual replacement of the pelitic and fine-grained detrital gray-colored sediments by the psammitic and psephitic red-colored rocks is also observable in the same direction. Changes in the depositional setting are accompanied by changes in the mineral composition as well: typical arkosic sediments in the northeastern parts of the section give place to oligomictic and quartz terrigenous mineral associations.

(3) The structure and interrelation of seismic sequences, as well as the composition and facies appearance of lithological varieties, characterize the stages in the tectono-depositional development history of the Province. Three stages in its formation are readily definable in the structure of the cataplatform cover (from the base upward): (1) main phase of the graben formation in the Central Russian and White Sea–Pinega regions; (2) terminal phase of the graben formation—initial phase of the postrift subsidence in all regions of the Province; and (3) formation of the non-riftogenic Orsha depression—"protosyneclise" in the Orsha region.

(4) Differences in the structure of the cataplatform megacomplex of the Central Russian–Belomorian province imply different tectonic and depositional histories of the development of several key structures.

The available structural, lithofacies, and seismostratigraphic data allow the Neoproterozoic tectono-depositional systems of the Central Russian and White Sea–Pinega regions to be considered as geodynamically conjugate structural elements of the craton: Central Russian–Belomorian tectonic pair. The tectonic pair evolved in the course of a single geodynamic process (but not single-stage), which created strain fields similar in energy, but differently oriented in neighboring regions. It is conceivable that the structures of the Central Russian–Belomorian tectonic pair under consideration characterize only a small part of the superregional system, whereas its significant part was reworked during the Paleozoic–Cenozoic stage of the Earth's history.

The Orsha depression differs from other tectono-depositional systems of the Province by a set of structural, facies, mineralogical, and seismic parameters, which cannot be explained by rifting (graben formation) or postrift subsidence.

The confinement of the depression to the specific domain of the Novgorod syntaxis and increment of the clinoform progradational sedimentary bodies in the N–S direction (from the assumed maximum compression area, i.e., Slobodskoi juncture) clearly indicated by the seismic exploration data allow the Orsha depression to be considered a compensatory basin that was formed during transition from the cataplatform megastage the East European Platform development to the othoplatform one.

[7] This must influence the initial attribution of barren sequences to the Middle or even Lower Riphean.

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