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Tectono-Depositional History of the Central Russian Aulacogen and Moscow Syneclise

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Abstract—The modern structure of the Central Russian region was formed by tight and long-term (hundreds of million years) interaction of tectonic and sedimentary processes in the upper crust and sedimentary cover. Petrophysical properties of the Paleoproterozoic crust predetermined the area for the development of regional strike-slip faults and aulacogen grabens in the Neoproterozoic. The transfer displacement of the aulacogen axis at the end of Riphean led to the partial erosion and redeposition of the preplate cover and caused the subsequent structural asymmetry of syneclise. The development of reversed structures in the plate cover (Sukhona mega swell) was caused by the slower subsidence of comparatively lighter fragments of the aulacogen crust relative to the surrounding frame.

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FORMULATON OF THE PROBLEM

The main volume of sedimentary cover of the central East European Platform is restricted to the Central Russian Aulacogen and Moscow Syneclise (Fig. 1). The aulacogen is a composite structure formed by a chain of fault-related grabens arranged along the axis of a larger syneclise.

These sedimentary basins have different nature: aulacogen is regarded as a preplate riftogenic structure of the Late Baikalian (Riphean—Early Vendian) craton destruction, while syneclise is a postrift depression of the Upper Vendian—Paleozoic plate stage of the platform evolution (Aksenov, 1998; Bogdanov, 1964; Fedorov et al., 1996; Garetskii, 1995, 2005; Garetskii et al., 2005; Khain, 1977; Kostyuchenko and Solodilov, 1997; Kropotkin et al., 1971; Milanovsky et al., 1994; Nagornyi, 1990; Shakhnovskii, 1988; Shatsky, 1964; and others). Of most interest is the transition period between these stages, when contrasting movements of the Earth's crust facilitated exhumation of the basement blocks to the erosion zone. Traces of these events should be recorded in variations of thickness, facies distribution, and mineral composition of deposits.

Many questions still remain regarding the character of tectonic movements and associated sedimentation settings. In spite of the obvious inheritance in the initiation of syneclise above aulacogen and established structural regularities of each sedimentary basin, it is yet unclear how preplate structures affected sedimentation settings of the plate stage of the platform evolution? It is also unknown which reasons caused the keyboard movements of the basement and associated partial erosion of the preplate cover on the Danilov—Lyubim area of the aulacogen, where the thickness of Riphean deposits was sharply reduced against the background of increasing thickness of Upper Vendian ones (Fig. 2). No explanation is also offered for the nature of the transfer displacement of the longitudinal aulacogen axis along the Rybinsk fault (Fig. 1). This displacement not only disturbs the linear structure of the aulacogen, but also split the syneclise into two sharply asymmetrical parts. West of the fault, the deepest basement unit is confined to a relatively narrow band of the Valdai and Molokovo grabens. East of the fault, basement depths of 2 or 3 km were established at a significant (few hundreds of kilometers) distance from the aulacogen axis and they mark the spacious southern Galich and northern Gryazovets troughs (Fig. 1). In addition, plate cover deformations found only in the eastern part of the syneclise form the large (Sukhona) megaswell above aulacogen grabens.

These questions can be solved by the consideration of genetically diverse sedimentary basins within a single tectono-depositional system with polygenetic and long-term (around 380 Ma) evolution. The tectono-depositional system is understood as a combination of processes and phenomena related to the structural formation and sedimentation. Only a joint study of structural and sedimentation aspects provides insight into the evolution of separate elements and entire system. In this case, many structural regularities of the plate cover can be coordinated with the structural organization and petrophysical properties of the underlying

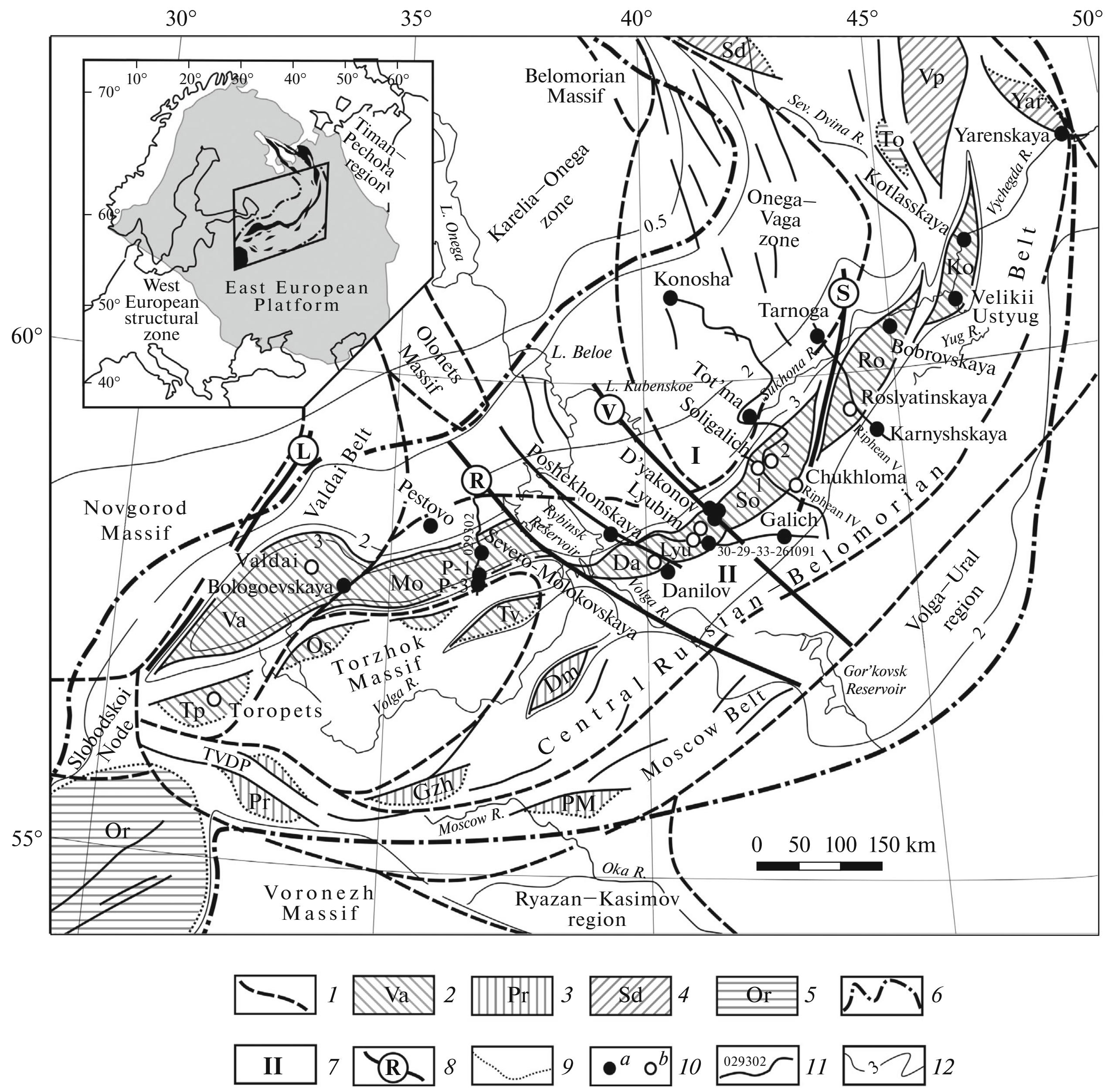

Fig. 1. The Central Russian region of the Central Russian–Belomorian province of the East European Platform. (*1*) Boundaries of lithotectonic complexes of the basement; (2–5) preplate tectono-depositional systems: (2–4) grabens: (*2*) Central Russian Aulacogen—(Va) Valdai, (Mo) Molokovo, (Tp) Toropets, (Os) Ostashkovo, (Tv) Tver, (Da) Danilov, (Lyu) Lyubim, (So) Soligalich, (Ro) Roslyatino, (Ko) Kotlas; (*3*) Moscow region—(Pr) Prechistinka, (Gzh) Gzhat, (Pm) Podmoskovnyi, (Dm) Dmitrov–Yaroslavl; (*4*) Belomorsk–Pinega—(Yar) Yarensky, (Vp) Verkhnyaya Pinega, (Sd) Severnaya Dvina; (*5*) basins—(Or) Orsha, (To) Upper Toem; (*6*) boundaries of the plate complex (Moscow–Mezen subsidence zone); (*7*) plate troughs: (I) Gryazovets, (II) Galich; (*8*) proved and inferred faults: (L) Lovat, (R) Rybin, (V) Vologda, (S) Sukhona; (*9*) lines of pinch out of sedimentray infill of the basins; (*10*) boreholes: (*a*) reaching the crystalline basement, (*b*) terminated in the Riphean deposits; (*11*) CMP seismic profiles; (*12*) isohypses of the basement surface, km (modified after *Gipsometricheskaya* ..., 2001). Inset shows the position of preplate tectonodepositional systems of the province in the East European Platform.

sedimentary complexes and rocks of consolidated crust.

In this work, the consideration of these questions is aimed at reconstructing the polygenetic history of a long-lived tectono-depositional system, which was initiated from aulacogen and transformed into syneclise. The attention is focused on the successive examination of the structure of aulacogen segments and their paleotectonic development, including possible tectono-depositional settings at different stages of aulacogen evolution, preplate tectonic revolution, and plate subsidence of the syneclise.

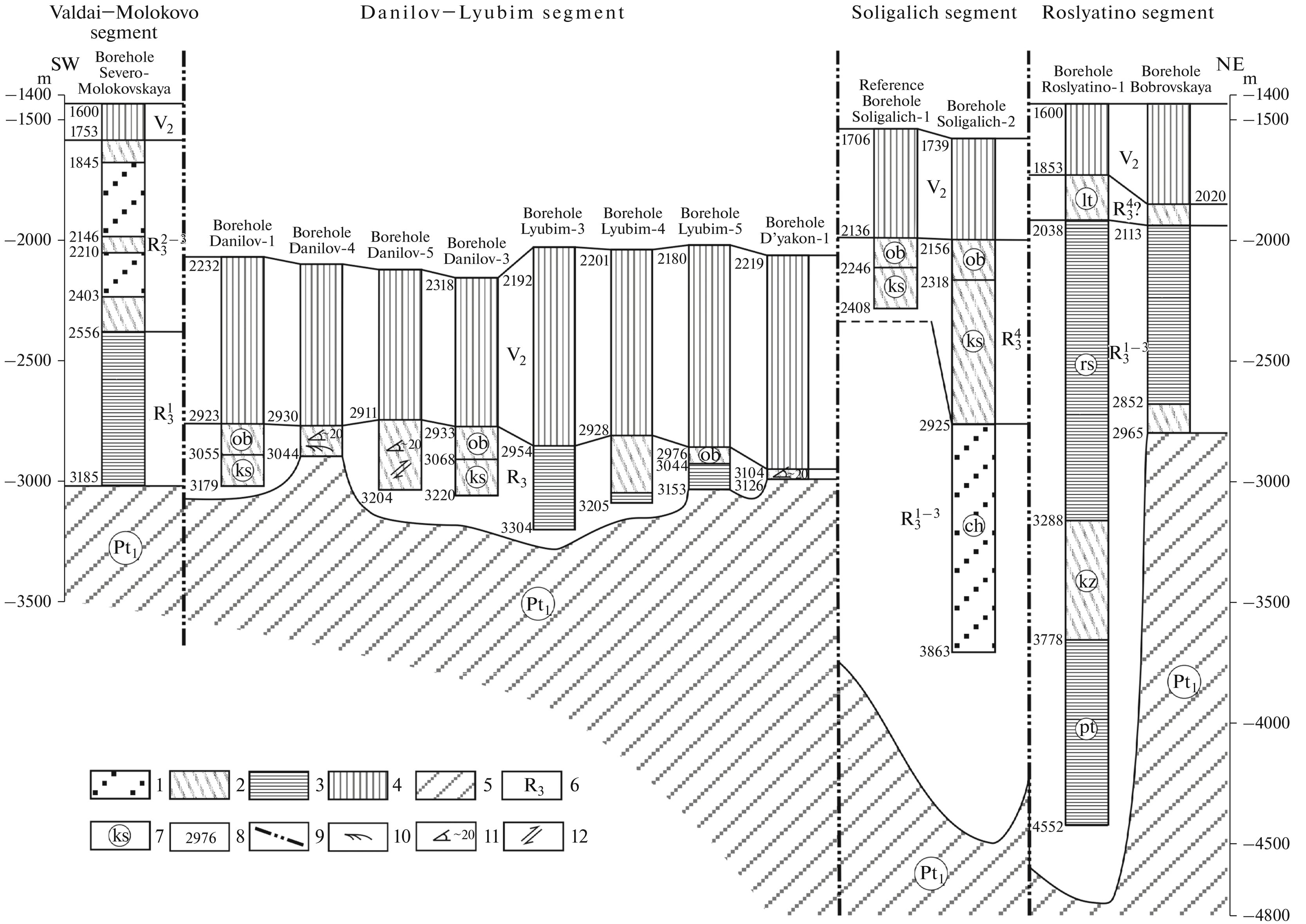

Fig. 2. Structure of Neoproterozoic sedimentary sections in different segments of the aulacogen. (1–4) Deposits: (1) red-colored gravelly–sandy, (2) variegated sandy–silty–clayey, (3) gray-colored silty-clayey, (4) undivided sandy–silty–clayey; (5) aulacogen crust; (6) seismocomplexes—(Pt_1) Lower Proterozoic basement, (R_3) Upper Riphean preplate, (V_2) Upper Vendian plate; (7) Formations—(ob) Obnor, (ks) Kostroma, (ch) Chuhloma, (lt) Litomin, (rs) Roslyatino, (kz) Kozhukhov, (pt) Putilov; (8) depth in boreholes, m; (9) boundary of segments; (10) cross-bedding; (11) angle of overturning of the parallel-bedded varieties; (12) slickenside. Position of borehole as in Fig. 1.

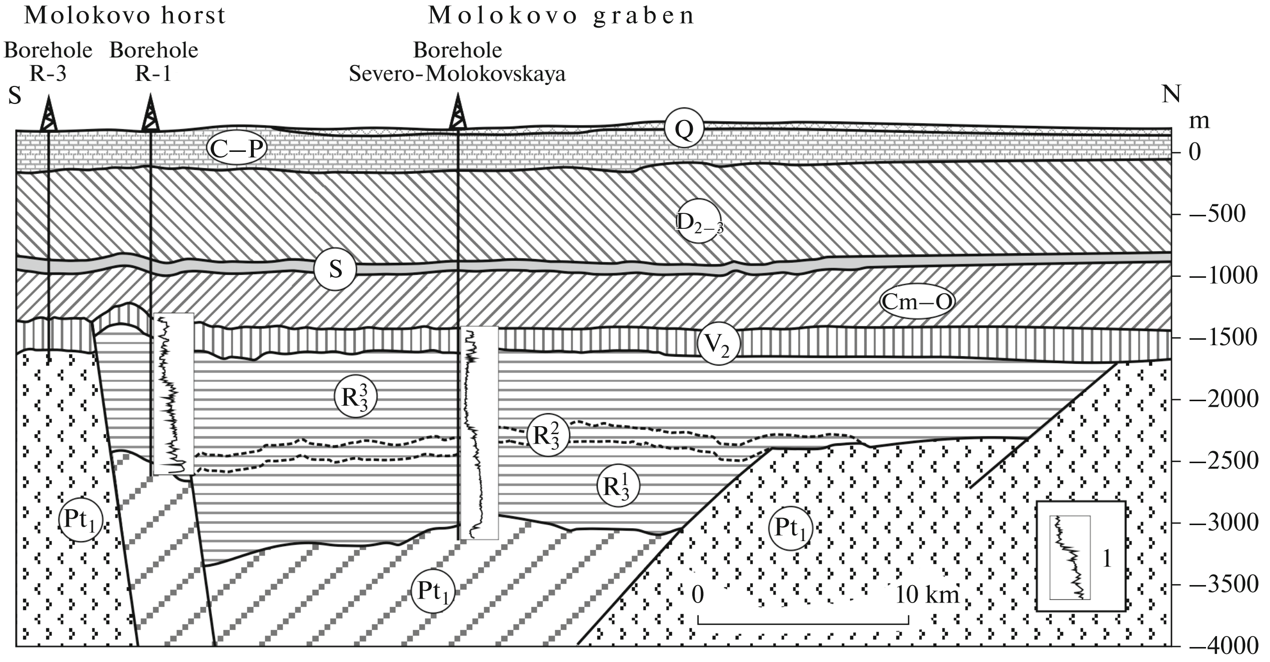

Fig. 3. Seimogeological section along fragment of the CPM 029302 profile (Tsvetkov et al., 2001). (1) SP logging curves, range −50 ... + 50 mV. Position of profile and boreholes as in Fig. 1.

STRUCTURE OF THE AULACOGEN SEGMENTS

Aulacogen grabens (except the Valdai graben) are developed in the central part of the Central Russian–Belomorian Belt (Fig. 1), which differs significantly in the petrophysical properties from terranes on both sides. Thickness of the lower crust in this area increases to 18–20 km, but the stratal velocity decreases to 6.8–6.9 km/s and the Moho depth varies from 39 to 42 km (Bush et al., 2002; Kostyuchenko et al., 1999). The stratal velocity is even lower in the upper crustal dynamometamorphosed rocks (blastomylonites). In particular, at the base of the Molokovo graben, the stratal velocity of seismic waves between the basement top and depth around 350 m is approximately 5.3 km/s. The low density (approximately 2.8 g/cm^3) of rocks in this low-velocity part of the basement is also confirmed by direct studies of the core of Borehole Severo-Molokovskaya drilled in the axial part of the graben (Tsvetkov et al., 2001). Similar pattern is also observed in the Tver graben, which is parallel to the Molokovo graben, where velocities near the basement top are as low as 4.9–5.0 km/s. The velocities of wave propagation on the graben flanks, in particular, in rocks of the Torzhok Massif, and beneath the low-velocity basement layer are 6.2–6.4 km/s (Tsvetkov et al., 2001). The characteristic feature of the belt is the clearly expressed "transparency" of magnetic field at the absence of prevailing directive arrangement of anomalies. The value of magnetization is less than 500 and even 300 × 10^6 CGS (Delyusin et al., 1970). Drilling revealed a wide distribution of weakly magnetic migmatites, microcline granodiorites, and blastomylonites after them in the belt (Chamov, 2016).

The structure of sedimentary cover is different in different grabens of the aulacogen (Fig. 2). The aulacogen is clearly subdivided into four segments, which differ in structure and thickness of sedimentary sequences, depths of the basement top, and boundary between the preplate (Upper Riphean) and plate (Upper Vendian–Paleozoic) deposits.

The *Valdai–Molokovo segment* extends from the Valdai Rise to the Rybinsk Reservoir (Fig. 1). The structure of eponymous grabens is determined by oppositely dipping normal faults (Fig. 3). In particular, the northern flank of the Molokovo graben is marked by faults with amplitude of approximately 500 and 900 m, while the total amplitude of normal faults at the southern flank reaches 2 km. It is clearly seen that the normal faults were formed at different times, while the graben was developed in at least two stages with prograde increasing of its width.

The *basement* lies at depths from 3 to 3.5 km. Its rocks are represented by migmatites after amphibolites with the characteristic steep dips of directive structures from 60°–65° to 75°–80° with respect to a plane orthogonal to the core axis. The migmatites are associated with blastomylonites, which form typical low-velocity (5.4–5.7 km/s) slices marking the Paleoproterozoic zones of intracrustal detachment (Chamov, 2016a).

The *preplate complex* has similar structure in all grabens of the segment and is described in detail in several publications as the Upper Riphean Molokovo Group (Chamov, 2016a; Tsvetkov et al., 2001). The sequence has a clear regressive structure with irreversible transition from the lower gray pelites to the upper red-colored psephites (Fig. 2). Facies features of the deposits indicate a change of lacustrine sedimentation by the prolluvial-alluvial setting of rift valleys. The appearance of the red-colored psephites is clearly expressed in the logging curves (Fig. 3). The boundary of these deposits is marked by a unit of intercalation of brown or gray sandstones, siltstones, and mudstones. Significant thickness of the unit (153 m in Severo-Molokovskaya and 362 m in Bologoevskaya boreholes), its expression in the CMP seismic profiles, and coincidence with the gradient of intensity values in the DS and PS diagrams gave grounds to consider it as the independent stratigraphic unit in the section of the Valdai—Molokovo segment (Tsvetkov et al., 2001). At the same time, it should be noted that the similar units of variegated deposits are present at all levels in the sequences of all segments of the aulacogen and are considered by us as the facies indicator of shallow-lacustrine sedimentation.

All sequences of the Molokovo Group are similar in composition and consist of feldspar—quartz oligomictic and arkosic sandstones, feldspar—quartz siltstones, and variably silty chlorite—hydromica—kaolinite mudstones (Chamov, 2016a). They also demonstrate the similar polycomponent composition of clayey matter in the sandy—silty deposits and mudstones. The general immaturity of sediments and characteristic presence of fragments of metamorphic basement rocks point to the proximity of sources of clastogenic material. The heavy fraction of the gray-colored and variegated arkosic sandstones contains epidote, hornblende, titanite, zircon, garnet, tourmaline, staurolite, and ore minerals. Some intervals of the gray-colored portions of the preplate section show a sharp enrichment of heavy fraction of sandstones in epidote from Early Paleoproterozoic blastomylonites. This phenomenon is observed over the entire aulacogen and considered in detail in (Chamov, 2015, 2016a).

The *plate complex* rests on the grabens and flanks of the aulacogen through erosion surface, which is gradually uplifted to the southwest and toward the Ladoga monocline of the Baltic Shield. In particular, the base of the plate complex (Upper Vendian "high-ohmic sequence") rests at a depth of −1455 m on the northern flank of the Molokovo graben (Borehole Pestovskaya), −1588 m in the axial part (Borehole Severo-Molokovskaya), and −1773 m on the southern flank (Borehole R-1).

Deformations of the plate cover have insignificant amplitudes. This can be exemplified by the Molokovo horst on the southern flank of the eponymous graben (Fig. 3). Tectonic mobility of this block at the preplate—plate stage boundary indicates a decrease of thickness of the Upper Vendian sequence in Borehole R-1, which recovered only sedimentary deposits of the second half of the Povarovka time (Ivashkovskii, 1972). Beyond this block, the Upper Vendian is represented by the Redkino (basal) and Povarovka formations. This indicates that the block on the southern flank of the Molokovo graben experienced uplifting and represents an erosion salient, at least up to the second half of the Late Vendian Povarovka time. Later movements of the block are confirmed by the fact that the "Molokovo folds" with amplitude of few tens of meters are traced in reflecting horizons confined to the Upper Ordovician, Middle and Upper Devonian, and Lower Cambrian deposits (Demin and Karadzhaev, 1973).

The *Danilov—Lyubim segment* is restricted to the Rybinsk—Vologda deformation band bounded by the eponymous faults, which are sharply discordant to the strike of the Central Russian aulacogen (Fig. 1).

In the deep model of the Moscow syneclise (Bush et al., 2002), the deformation band is clearly traced up to the boundary with the Volga—Ural zone. The depth of the crust base within it varies from 38 to 42 km. Two local Moho offsets were established at the junction of the band with the Moscow Belt. Within the aulacogen, the shallowest Moho is observed beneath the Danilov graben and at the boundary of the Lyubim and Soligalich grabens near the cluster of boreholes in the D'yakonov area (Fig. 1). Other grabens of the Central Russian Aulacogen are not confined to areas with the thinned crust.

Amplitude of the dextral displacement of the Danilov—Lyubim segment along the Rybinsk fault relative to the Valdai—Molokovo segment exceeds 100 km. Primary structures of the Danilov and Lyubim grabens are strongly distorted by later crustal movements of different amplitudes (Fig. 4). The CMP seismic section along profile III "Rifei" displays a package of reflections, which can be interpreted as fold—block deformations. The basement is subdivided into numerous small blocks with surface depths from −2890 m to more than −3200 m. It is believed (Panchenko, 1975; Usanov, 1979) that the uneven erosion of some part of the preplate cover is related to movements of these blocks in the pre-Vendian time.

The *basement* is recovered by boreholes Danilov-4 and Danilov-7 at a depth of −2890 m and −3019 m, respectively. The core consists of brownish gray and greenish gray inequigranular schistose quartzite- and granite-gneisses with light gray quartz pockets. The core of Borehole Danilov-7 demonstrates migmatite banding of two generations: early melanocratic banding at an angle of 45°—50° and cross-cutting banding at an angle of 60°—70° to the horizon. The degree of weathering increases upsection, and the basement rocks near the contact with gray-colored sedimentary deposits include leaching caverns and acquire dull tint

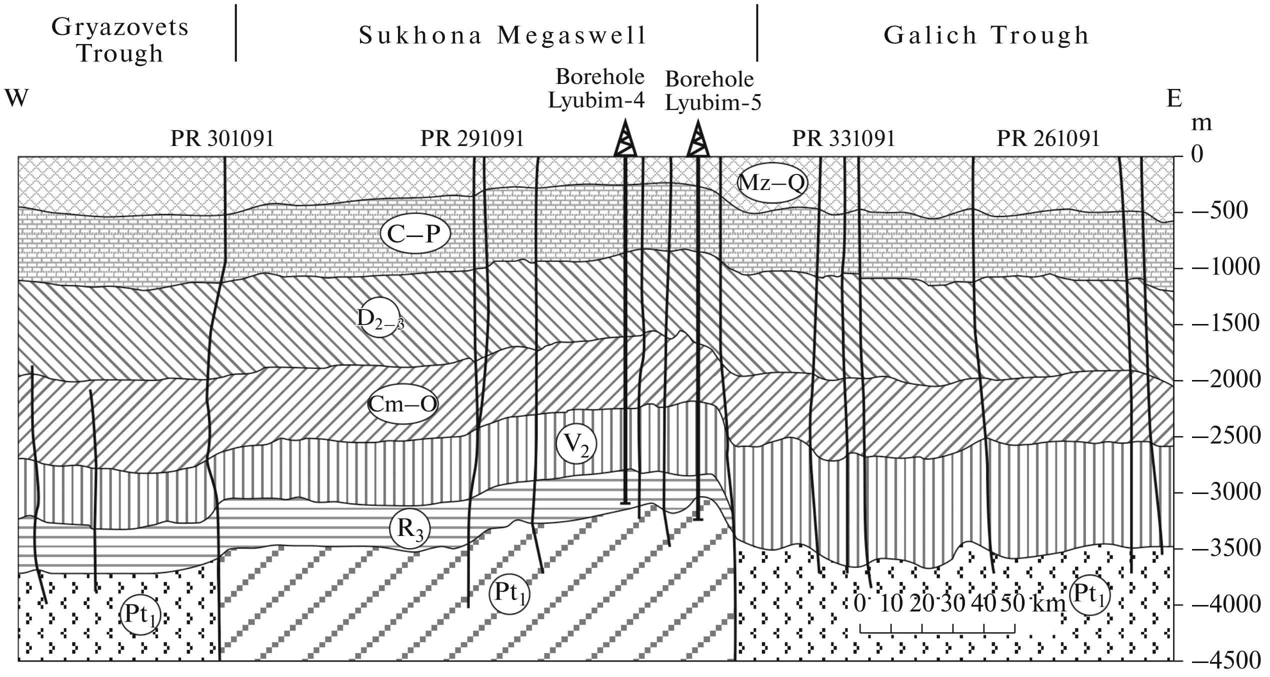

Fig. 4. Seismogeological section along fragment of the composite CMP30-29-33-261091 profile (Burganov et al., 1994). Position of profile and boreholes as in Fig. 1.

and light green color. The rock consists of quartz (30%), altered cordierite (25%), plagioclase (22%), K-feldspars (10%), garnet (6%), and biotite (3%) (Usanov, 1979).

Borehole Lyubim-5 at a depth of –3034 m recovered dark gray and gray weathered (near the roof) garnet–biotite and sillimanite–biotite plagiogneisses with directive structures dipping at angle of 60°–70° and signs of migmatitzation and cataclasis. The rocks consist of quartz (45%), feldspar (30%), biotite (10%), microcline (7%), sillimanite (up to 18%), and garnet (6%) (Kagramanyan et al., 1975).

Prospecting boreholes D'yakonov 1 and D'yakonov 3 recovered the basement at depths around –3000 m. It is made up of garnet–biotite plagiogneisses, which are highly weathered in the upper part. The major minerals are plagioclase (up to 30%), quartz (27–32%), biotite (27%), garnet (7–18%), and K-feldspar (9%); the subordinate components are ore minerals, zircon, and apatite. Garnet grains are frequently large and irregularly shaped. Quartz is present as irregular (sometimes elongated) grains, lenticules, and poikilitic ingrowths. It shows sharply expressed wavy extinction. The rocks are strongly fractured with fractures and layers inclined at 85° (Borehole 1) and 60°–70° (Borehole 3) to the horizontal. The fractures are filled with quartz and chlorite (Panchenko, 1975).

The *preplate complex* in grabens of the segment has the least (residual) thickness as compared to other segments of the aulacogen (Fig. 2).

Boreholes in the Danilov area recovered Riphean deposits up to 114 m (Borehole Danilov-4) and 293 m (Borehole Danilov-5) thick. The sequence is made up of variegated (brown, pinkish) and gray-colored (bluish and dark gray) terrigenous sandstones and siltstones (Usanov, 1979). It is subdivided into several psammitic and pelitic units from tens of centimeters to few tens of meters thick. Within the units, the thickness of layers and interlayers varies from a few centimeters to a few meters thick. The sandstones and siltstones are inequigranular. They contain quartz and feldspathic pebbles up to 1–3 cm in size, as well as lenses and interlayers of gravelstones up to 15 cm thick. The clastic material is angular and unsorted. Sandy varieties show cross- and cross-wavy bedding, with variable bedding angles. Inclination between the parallel bedding and the plane perpendicular to core axis reaches 20°. Slickensides were established in separate intervals of the section. They have feldspar–quartz, more rarely quartz–feldspathic composition (quartz from 35 to 92%, feldspar from 5 to 30%). The cement is a basal-porous, basal, clayey-pellicular, and clayey–chloritic material of the hydromica–kaolinite or clayey composition with iron hydroxides. Banding of separate beds is caused by the accumulation of clay material.

Boreholes in the Lyubim area recovered the Riphean sedimentary complexes with thickness ranging from 159 m (Borehole Lyubim-6) to 382 m (Borehole Lyubim-3) (Fig. 2). The section is made up mainly of dark brown, violet-dark brown, more rarely bluish and light gray inequigranular quartz–feldspar deposits locally grading into gravelstones (more rarely, conglomerates). Interlayers and lenses of dark brown, more rarely dark gray and greenish to light gray siltstones and mudstones occur in subordinate amounts. Sandstones consist of the clastic material (65%) mainly represented by quartz, as well as plagioclase and, more rarely, microcline and mica. The feldspar (plagioclase) grains are unevenly sericitized and chloritized. They have angular and subangular (more rarely, corroded) shape. They have pore filling and contact cement of clay composition (kaolinite and possibly chlorite saturated in iron hydroxides). Accessory minerals are tourmaline, garnet, zircon, and epidote-group minerals (grains from 0.1–1 to 2 mm) (Kagramanyan et al., 1975).

Prospecting boreholes D'yakonov 1, D'yakonov 2, and D'yakonov 4 recovered the preplate complex with the maximum thickness of 88 m (Borehole D'yakonovo-2). The preplate complexes recovered completely by Borehole 1 (22 m) lie on the basement rocks (Panchenko, 1975). Bedding angles show significant variations along the core. According to V.A. Lapchenko, this fact indicates the presence of smaller structural units in the Riphean structural stage. He also puts forth a problem of the origin of Riphean deposits: "...it is presently unclear whether the Riphean deposits lying on the uplifted basement blocks are coeval with the Riphean basal layers or they were formed simultaneously with later Riphean complexes, being result of the general subsidence or uplifting of these blocks" (Panchenko, 1975, p. 113). This problem will be considered below.

The section consists of the poorly sorted variegated psammitic, frequently gravelly deposits varieties with interlayers of red-colored mudstones, gravelly conglomerates, and siltstones. Bedding surfaces are emphasized by mica accumulations. In all sections, especially near the roof zone, the clastic part and cement are calcitized. The gravelly–pebbly material is represented by weakly rounded fragments of quartzites, feldspars, and basement rocks. The sandstones are weakly sorted and contain enclaves of gravel and pebble. The clastic material is angular and unevenly rounded. The cement in sandstones is clayey, basal, and more rarely pellicular and ferruginated. The deposits contain quartz (50–90%), feldspars (5–40%), fragments of rocks (up to 10%), and micas (up to 1%). Sandstones show wide variations in mineral proportions, which indicate variability in the direction and provenances (Panchenko, 1975).

The *plate complex* sharply differs from other segments of the aulacogen in terms of some features. First, it is located at depths from –2800 to –3000 m, which is much deeper than the depth (from –1600 to –2000 m) in other segments (Fig. 2). Second, thickness of the Upper Vendian sequence only in this segment is approximately 700 m in the Danilov and up to 900 m in the Lyubim grabens. Third, only this segment is characterized by significant thickness (up to 1000 m) of the Cambrian–Ordovician deposits, which are reduced or absent in other segments.

The CMP seismograms of the auolacogen sections show conformable uplifting of reflections of the basement roof and all elements of sedimentary cover in the area of boreholes Lyubim-4 and Lyubim-5 (Fig. 4). The observed antiform with amplitudes of 100–150 m is ascribed to a large structure of plate cover: Sukhona (Rybinsk–Sukhona, Soligalich–Sukhona) megaswell, which was first established by E.M. Lyutkevich based on measurements of bedding in the Sukhona exposures. In plan, the megaswell represents a narrow horst separating the Gryazevets and Galich troughs. At a width of around 50 km, it is extended in the northeastern direction from the town of Danilov to the Roslyatino and Bobrovskii Settlements, where the megaswell gradually goes down and completely disappears (*Geologiya* ..., 1985). The megaswell unites a system of elongated asymmetric swells, which, in turn, consist of lenticular and echeloned rises (Roslyatino, Zelentsovo, Bobrovskoe, and others). The swell limbs are complicated by flexures with the dip of layers up to 5°–6° or more. The flexures fix the flank faults bounding the aulacogen (Buslovich, 2008; Delyusin et al., 1970). It is noteworthy that the flexure of sedimentary cover in all blocks is confined to the steepest walls of the basement basin (Delyusin et al., 1970).

The *Soligalich segment* is extended along the Sukhona River from the Vologda fault to the Sukhona fault in the northeast (Fig. 1). The primary structure of the Soligalich graben is distorted, and its reconstruction requires special considerations.

Unlike the Danilov–Lyubim segment, the CMP seismogram displays large reversed[1] structure with visible thickness around 90 km or no less than 70 km with allowance for the nonlinear drawing of profile (Fig. 5). Most part of the structure is disturbed by faults. The total vertical displacement of the Vendian base is 1300 m along the southern fault and 950 m along the northern fault. In the central part of the segment, thickness of the preplate complex exceeds 1700 m, but sharply decreases (up to 900–1000 m) toward flank faults. To the south and north of flank faults of the aulacogen, a supposedly Riphean unit is distinguished between the basement and the foot of Vendian deposits (Shamov and Burganov, 1999). Near the flank faults, these deposits are around 1 km thick. To the north and south of the aulacogen at a distance around 15 km, their

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[1] Reversed structures are referred to anticlinal forms in the plate cover (swell) located above the negative structures of the basement. Descriptive definition "reversed structure" seems to be wider and, therefore, more preferable than "inverted structure" frequently applied to such forms. The latter has a strict genetic interpretation, determining the change of directions of tectonic displacements into reverse one as the main structural-forming factor (*Tolkovyi* ..., 2002). It will be shown below that the inversion movements were not necessary conditions for the formation of the Soligalich and Roslyatino reversed structures.

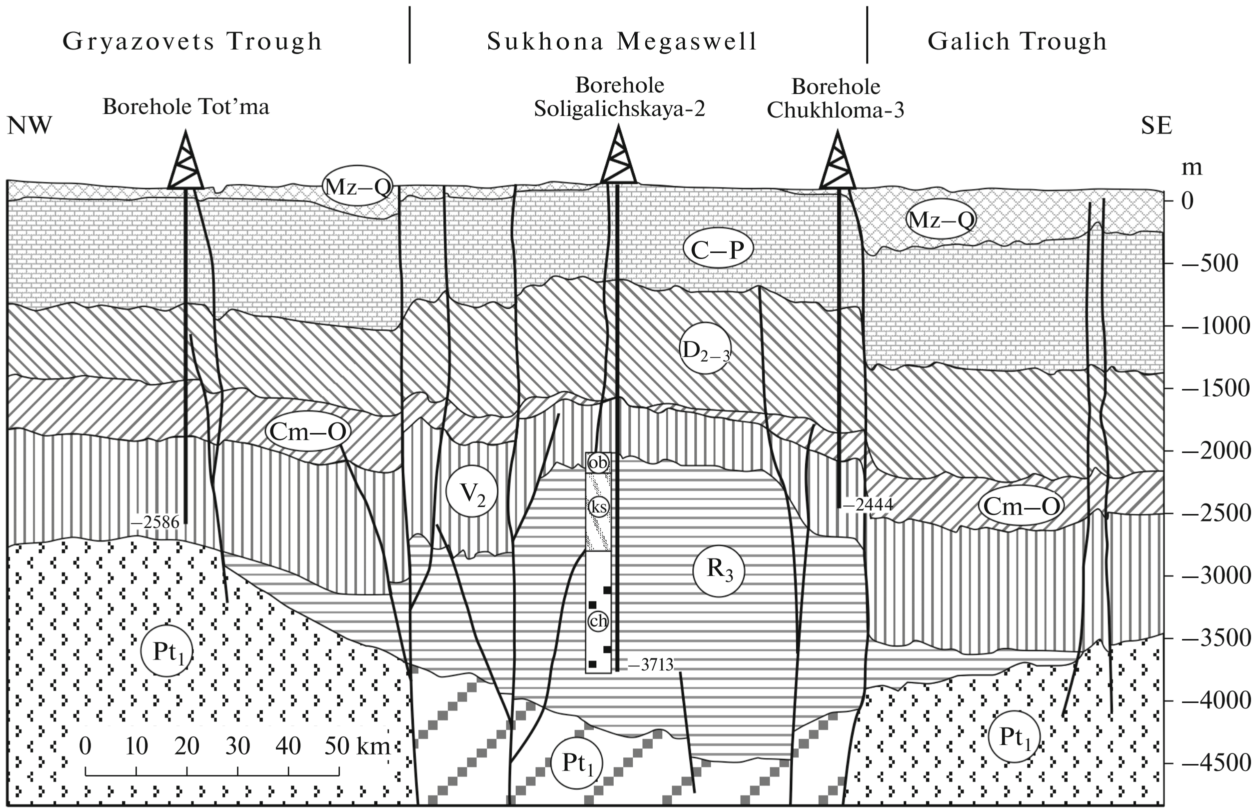

Fig. 5. Seismogeological section along fragment of the CMP IV–IV profile (Shamov and Burganov, 1999). Symbols are shown in Fig. 2. Position of the profile and boreholes as in Fig. 1.

thickness gradually decreases to complete pinchout (Fig. 5).

The *basement* was not recovered by drilling. According to the seismic survey, it is suggested at depths up to –4500 m (Shamov, 2001).

The *preplate complex* differs from other segments of the aulacogen in lithology of the recovered part (Fig. 2). Drilling of Borehole Soligach-2 established three units of coarse-clastic psammitic deposits.

Upper unit (2156–2318 m, Obnorskaya Formation^2) is represented by the fine- to medium-grained pinkish brown feldspar–quartz sandstones with thin siltstone inerlayers. The main mineral of heavy fraction is garnet (Zolotov et al., 1971).

Middle unit (2318–2925 m, Kostroma Formation) consists mainly of the red-colored fine-grained mica–quartz–feldspar sandstones. There are also subordinate inequigranular sandstones in the upper part of the unit and interlayers of reddish brown and rarer greenish gray highly micaceous mudstones in the lower part. The sandstones have hydromica, kaolinite, chlorite, and ferruginous cement. The heavy fraction, in addition to garnet, contains widespread epidote, titanite, and less common rutile and black ore minerals.

Lower unit (2925–3863 m, Chukhloma Formation) is distinguished by the coarser grained composition of clastic material. This unit consists mainly of the red-colored coarse-grained arkosic sandstones, gravelstones, and breccias cemented by clayey and clayey–chlorite material. The clastic material is poorly sorted and angular, which indicates proximity to source area. Heavy-fraction minerals are dominated by garnet and black ore minerals. The content of anatase increases, whereas titanite, epidote, and rutile disappear almost completely.

In the adjacent reference Borehole Soligalich-1, the upper unit occurs in the interval of 2136–2246 m; i.e., this unit is reduced in thickness as compared to that in Borehole Soligalich-2 (according to materials of Z.P. Ivanova and V.V. Kirsanov) (Fig. 2). Sandstones are red-brown, brown (sometimes white), fine- and inequigranular, locally with layers of gravel grains and subordinate interlayers of red micaceos siltstones and mudstones. Typical mineralogical complex includes garnet, ilmenite, magnetite, brown iron hydroxides, epidote, titanite, and biotite. The content of feldspars is high. Drilling was stopped in deposits of the middle unit at a depth of –2263 m. Sandstones are violet-brown, coarse- and medium-grained with intercalations of micaceous siltstones, green, and brown mudstones. Typical mineralogical complex is

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[2] The terms of formations are given after (Kirsanov, 1970).

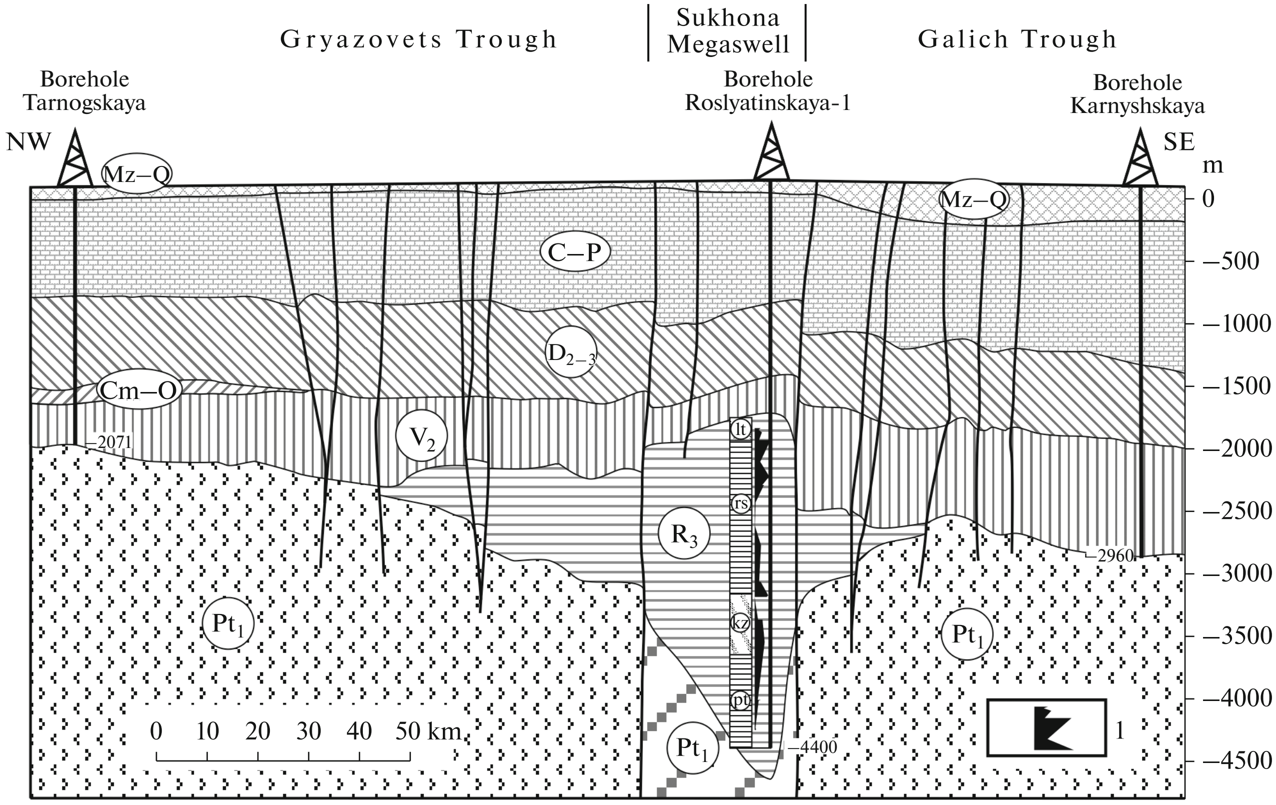

Fig. 6. Seismogeological section along the CMP V–V profile (Shamov, 2001a). (1) Intervals with elevated epidote content in the heavy fraction (Chamov, 2015). Other symbols are shown in Fig. 2. Position of profile and boreholes as in Fig. 1.

epidote, garnet, ilmenite, and magnetite. There are also brown iron hydroxides, titanite, muscovite, and feldspars.

Noteworthy is the position of boundaries of sedimentary complexes recovered by drilling relative to structural elements of the preplate reversed structure. In particular, the upper unit is confined to the roof, while the contact between the middle and lower units is located at a level of bending in its middle part (Fig. 5).

The *plate complex* of the segment composes the upper part of the reversed structure in the Soligalich megaswell. Positive deformations clearly observed in all horizons of the plate cover in CMP seismograms are virtually conformable to the roof of the Riphean sedimentary complex (Fig. 5). At the same time, decrease of thickness or complete disappearance of some deposits indicates the multistage and long-term evolution of these deformations.

The structure of the adjacent Gryazovets and Galich troughs reflects different dynamics and disagreement in the subsidence time. A great depth (around −3500 m) of the Galich Trough versus −3100 m in the Gryazovets Trough is responsible for the highest amplitudes of displacements along the southern flank fault.

The *Roslyatino segment* is located northeast of the Soligalich segment, traced from the Roslyatino Settlement to the Bobrovsky Settlement, and recovered by eponymous boreholes (Fig. 1). The visible width of the segment bounded in the cross-section by flank faults of the aulacogen is around 50 km (Fig. 6).

In spite of the deformation, the primary structure of the Roslyatino graben is traced with confidence. Steep southeastern and gentler stepped northwestern flanks determine the characteristic structure of half-graben. Displacement amplitudes along the flank faults are 550 m for the northwestern flank and 850 m for the southeastern flank. Note that the subsidence depths of Vendian deposits in adjacent areas are much lower than that of the Soligalich segment (−2200 m from the side of the Gryazovets Trough and −2500 m from the side of the Galich Trough).

The *basement* is not recovered by drilling. Borehole Roslyatino was stopped in the Riphean deposits at a depth of −4400 m, while the basement surface according to TEM sounding is suggested at a depth of −4750 m (Delyusin et al., 1970). At a depth of −2794[3] m, parametric Borehole Bobrovskaya-1 recovered the fine- and coarse-crystalline gabbrodiabases with signs of retrograde metamorphism (Eremenko, 1974).

The *preplate complex* has the highest thickness (2699 m) in the aulacogen (Fig. 2). Due to the asym-

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[3] After (*Gipsometricheskaya* ..., 2001).

metric structure of the graben, the Riphean deposits pinchout rapidly in the northwestern direction (Fig. 6). The quality of seismic data does not allow us to state unambiguously whether the Riphean deposits are present southeast of the main flank fault. Based on the Borehole Roslyatino-1 data, the section consists of six Riphean units[4].

Unit 6 (1853–2038 m, Litomin Formation[5]) is represented by the alternation of sandstones, siltstones, and mudstones. They have brown, dark brown, reddish brown, and rarely greenish gray color. Sandstones are medium to fine-grained, laminated, and massive. The deposits consist of quartz (70–80%), feldspars (10%), micas, accessories (titanite, epidote, and Ti-bearing garnet), ore minerals, and chlorites.

Unit 5 (2038–2176 m, upper part of the Roslyatino Formation) is made up of gray siltstones and mudstones. The subordinate sandstones are highly and moderately sorted deposits with quartz (50%), fragments of siliceous and clay sediments (up to 40%), mica flakes (10–20%), grains of feldspars (10–20%), chlorite, and epidote.

Unit 4 (2176–2702 m, middle part of the Roslyatino Formation) consists of gray, greenish gray siltstones and mudstones with interlayers and intercalations of sandstones. The sandstones contain quartz (75–90%), feldspars (plagioclase and microcline), calcite, quartzite, micas, accessories (epidote 60%, garnet, zircon), and ore minerals.

Unit 3 (2702–3288 m, lower part of the Roslyatino Formation) is mainly made up of greenish gray mudstones with thin intercalations of sandstones and siltstones. The siltstones are greenish–dark gray, coarse-grained, micaceous, laminated, well-sorted. There are also thin interlayers and lenses of light gray and greenish gray quartz fine-grained micaceous sandstones. The clastic constituent of the siltstones is made up of quartz, mica, chlorite, feldspars, and accessory minerals (epidote 35–45% to 60%, garnet, zircon). Micas are represented by biotite (prevailing) and muscovite.

Unit 2 (3288–3778 m, Kozhukhov Formation) comprises sandstones, siltstones, and mudstones. The siltstones are greenish dark gray and dark brown. The sandstones are green-gray, gray, brownish red, fine- and medium-grained, micaceous, moderately sorted deposits. Clastic components are represented by quartz, feldspars, and accessory minerals (epidote 25–35%; titanite, garnet, zircon, zoisite, chlorite, and minor micas).

Unit 1 (3778–4552 m, Putilovskaya Formation) consists of mudstones with thin (3–5 cm) sandstone intercalations. The mudstones are green-gray, dark gray to black, micaceous, thin-bedded deposits sometimes grading into siltstones. The sandstones are light gray, greenish gray, fine and medium-grained, locally cross-bedded. Clastic components are dominated by quartz, with insignificant admixture of feldspars (plagioclase and microcline), micas, accessory minerals (epidote up to 50%, titanite, and garnet) and fragments of diverse crystalline rocks.

Riphean section of similar structure (945 m thick) was recovered by the parametric Borehole Bobrovskaya-1 on the northeastern flank of the segment (Eremenko, 1974).

The *plate complex* of the segment composes the upper part of the reversed structure in the Sukhona megaswell. Upward bending of beds conformable to the roof of the Riphean sedimentary complex is observed in all horizons of the plate cover directly above the graben (Fig. 6). As for the Soligalich segment, these forms are frequently considered as the result of inversion processes. Owing to the fact that the base of the plate complex occupies the hypsometrically highest position within the Sukhona aulacogen, some researchers believe the largest scale of inversion for the Roslyatino graben (Bush et al., 2002; Kuzmenko et al., 1991).

Concepts on the inversion nature of the Roslyatino reversed structure and other elements of the Sukhona megaswell are controversial and will be considered below. In this section, we are focused only on two points related to the structure of the Roslyatino antiform: sharp reduction of thickness of the Upper Vendian section above the most prominent part of Riphean deposits (Fig. 6) and disagreement between viewpoints concerning the position of the Riphean roof. According to M.I. Ostrov-skii, the latter is located at a depth of −1701 m (1853 m along borehole) (Zolotov et al., 1971). Previously, V.N. Delyusin ascribed the position of the Riphean roof to a mark of −2008 m (2160 m along borehole), because this depth corresponds to the lowest clear reference horizon in the SP electrical logging diagram (Delyusin et al., 1970). Another argument of V.N. Delyusin was related to the general geological structure: if the Riphean roof occurs at a depth of −2008 m, it is 500–600 m higher than flanks. This value coincides with the full amplitude of the elevation of the Sukhona megaswell (in the given cross-section) along the base of the Kazanian sequence at − 483 m (along boreholes 23-n and 11-s).

As seen from the section (Figs. 2, 6), most part of the controversial interval consists of deposits of unit 6, which was regarded by V.V. Kirsanov (1970) as the Litomin Formation of the Roslyatino Group. This formation is not correlated with the Riphean deposits in the adjacent segments of aulacogen. However, judging from the facies and mineral-petrographic composition

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[4] Given after (Gorbachev, 1973) and author's study of the core.

[5] Names of the formations are given according to (Kirsanov, 1970). Exception is unit 2, which was distinguished by Kirsanov as the Obnorskaya Formation. The section of the Roslyatino Formation is not correlated with that of the Dailov–Lyubim segment, where the Obnorskaya Formation is widespread. To prevent incorrect associations in the paper, unit 2 is correlated with the Kozhukhov Formation distinguished within the Riphean Vologda Group after Klevtsova (1971).

(see the description of sequence), it could be ascribed to the Vendian. In this case, the Vendian base in the Roslyatino structure was leveled owing to the increase of thickness (at least, by 185 m), while amplitude of the so-called inversion would be reduced by this value. This interpretation, first, takes into account the valid comments by V.N. Delyusin and, second, answers the reasonable question: why the maximum inversion is observed above graben with the lesser (as compared to the adjacent segments) volume of accumulated deposits, although external factors are similar?

Primary Structure of the Soligalich and Roslyatino Sedimentary Basins and Development of Reversed Structures

The above data on the modern structure of aulacogen segments reflect different degrees of the deformation of primary graben structures. In particular, grabens of the Valdai–Molokovo segment did not experience significant changes after their formation. In contrast, the Danilov–Lyubim segment contains relicts of graben structures subjected to uplifting and intense erosion at the preplate stage. Sedimentary basins of the Soligalich and Roslyatino segments have the most specific form. They escaped erosion at the preplate stage, but were significantly disturbed by later processes with the appearance of reversed structures in the sedimentary cover. As mentioned above, special considerations are required to understand the primary structure of these segments. For this purpose, we compiled the paleostructural sections using the leveling method for four reference seismostratigraphic surfaces by bottom and roof of the Upper Vendian, as well as roof of the Cambrian–Ordovician and Devonian sequences (Fig. 7).

In the paleostructural section of the Soligalich segment for the end of Riphean (termination of accumulation of the preplate cover), the modern seismocomplex R_3 (Fig. 5) is transformed into asymmetrical structure resembling a hat turned upside down (Fig. 7a). Three noteworthy elements of this structure are distinguished. The upper element (“fields of hat”) made up of deposits of the upper and middle units has a typical appearance of sag basins: at a visible width up to 185 km, it shows no fault restrictions, pinches out near the Riphean surface, and forms a gentle sag to a depth of –769 m. Pinching out of deposits of the upper unit toward the basin center is also reflected in a decrease of its thickness in Borehole Soligalich-1 (110 m) as compared to Borehole Soligalich-2 (165 m). The width of the middle element accounts for around 100 km, while its lower boundary is determined at depths from –1100 m (northern flank) to –1400 m (southern flank). Correspondingly, the lower element (up to 70 km wide) is located at depths from –1400 m to –2400 m. Both middle and lower elements have rectangular limitations typical of planar normal faults. The southern normal faults are characterized by great amplitudes and steep dip angles. As shown above, asymmetrical grabens of the Valdai–Molokovo segment have similar structure (Fig. 3).

Interrelations of elements in the paleostructural profile indicate that the Soligalich structure was formed by diverse mechanisms during at least three stages. The first and second stages were determined by normal faulting with the formation of graben and its subsequent lateral expansion. The third stage was dominated by syneclise-type processes with the formation of gentle sag depression. Such stagewise evolution is typical of sedimentary basins in the Central Russian–Belomorian province (Chamov, 2016a, 2016b).

Two-stage extension in the aulacogen grabens is clearly expressed in the structure of the preplate complex of the Valdai–Molokovo segment, where the gray-colored pelite–psammite deposits are overlain over a wider area by the red-colored psephites (seismocomplex R_3^{2-3}) (Fig. 2). In terms of structural position, facies appearance, and mineral-petrographic composition, the latter seismocomplex completely corresponds in the Soligalich section to the coarse-grained red-colored deposits of the lower recovered Chukhloma Formation, which are not correlated with the adjacent stratigraphic units (Fig. 7a). Although Borehole Soligalich-2 did not recover the full Riphean section, data on the pshephite complex suggest that the lower part of the graben consists of lacustrine gray-colored and/or variegated deposits. This statement is consistent with structural regularities of preplate sections in other grabens of the aulacogen. Thickness of the Riphean section (visible in the profile but not recovered by drilling) is 600–700 m, which is comparable with thickness of the lower element of the Molokovo Group (R_3^1) in other grabens of the aulacogen.

Based on the absence of structural limitations, pinchout of deposits from the core to the periphery of sag areas, and most mature composition of sediments, the upper synform part of the Soligalich structure can be correlated (although on a reduced scale) with the Orsha Basin previously classified as a “protosyneclise” (Chamov, 2016a, 2016b).

The composite profile Riphean IV has a complex configuration. Therefore, the inferred boundaries of sedimentary complexes shown in Fig. 7a should be considered as approximation to the real geological setting (working model). However, this model: (1) is based on the CPM seismic survey data; (2) is consistent with the drilling results; and (3) agrees with stages established for the evolution of sedimentary basins in the Central Russian–Belomorian province.

In the paleostructural section of the Roslyatino segment for the end of Riphean, the modern seismocomplex R_3 (Fig. 6) is transformed into a sharply asymmetrical graben with steep southeastern (main normal fault) and gentler stepped northwestern flanks

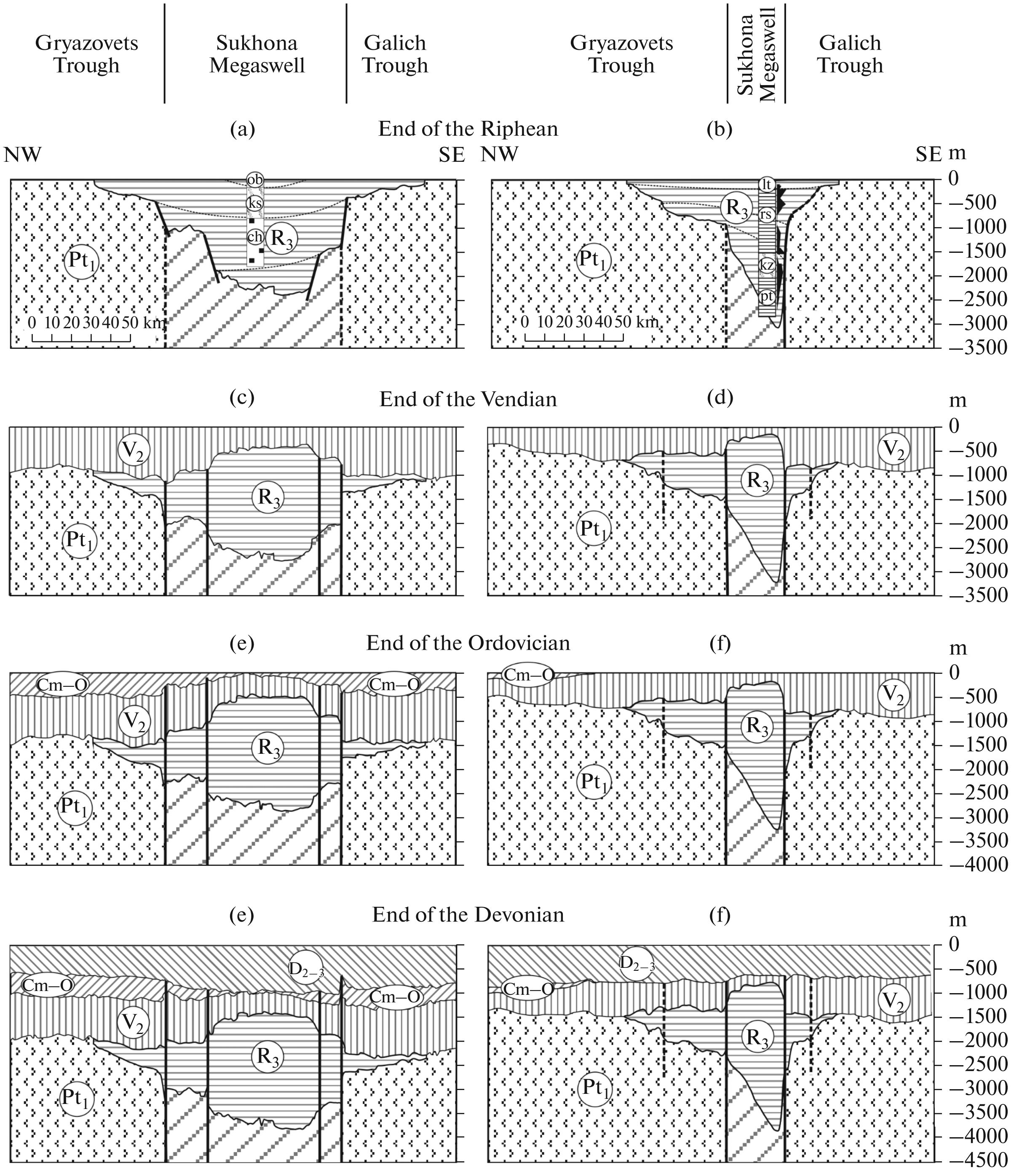

Fig. 7. Paleostructural sections of the Soligalich and Roslyatino segments along fragments of the CMP IV–IV and V–V profiles (Figs. 5, 6). Leveling along: (a, b) bottom of V_2 (end of Riphean); (c, d) roof of V_2 (end of Vendian); (e, f) roof of Cm–O (end of Ordovician); (g, h) roof of D_3fm (end of Devonian). Symbols are shown in Fig. 2. Position of profiles and boreholes as in Fig. 1.

(Fig. 7b). The structure of the graben reflects its prograde expansion with the growth. The graben structure is subdivided into the lower and upper parts. The lower thickest (2150 m) part is located within the depth interval from –925 m to –3075 m. It has a clearly wedge-type shape with rapid pinchout downsection from 30 km to the complete disappearance. Width of its upper part (925 m thick) varies from 100–110 km at the roof to 30 km at the base.

The model of the evolution of the Roslyatino graben is reported in detail in (Chamov, 2015, 2016a). Of most importance in the context of this paper are the following points. Morphology and depth of the Roslyatino graben are determined by the evolution of the

Table 1. Thickness of seismocomplexes in the aulacogen segments

Seismocomplex	Segments of aulacogen and thickness of seismocomplexes, m			
	Valdai–Molokovo	Danilov–Lyubim	Soligalich	Roslyatino
Upper Riphean (R_3)	1430	180	2500	3050
Upper Vendian (V_2)	150	680	420	250
Cambrian–Ordovician (Cm-O)	500	530	50	0
Silurian (S)	50	0	0	0
Devonian (D)	760	800	920	630
Carboniferous–Permian (C-P)	270	590	720	920
Triassic–Holocene (T-Q)	30	260	50	50

Neoproterozoic normal fault along the steeply dipping Paleoproterozoic slice of blastomylonites. Subsequent deepening of the Roslyatino graben not only did not lead to the isolation of the blastomylonite slice, but even stimulated its erosion. Against the background of stable mineral composition of deposits in the sequence, it shows at least three cycles of sharp enrichment (up to 70%) of the heavy fraction in angular epidote grains (Fig. 7b). Enrichment cycles reflect intensification of the erosion of local source and can be considered as markers of normal faulting, each of which led to the subsequent deepening and widening of the structure. Reconstructions of intermediate positions of the bottom of the basin are well consistent with the structure of the graben and its sedimentary infill. As seen from the Borehole Roslyatino section reduced to the graben paleostructure, the assumed surfaces of the bottom of the basin (dashed lines) correspond to the boundaries between lithological units: third and fourth, as well as fourth and fifth (Fig. 7b). The bottom of the upper part of unit 6 (Litomin Formation) can be taken as the base of the postrift sag basin.

Comparison of the paleostructural sections of the Soligalich and Roslyatino segments shows their significant differences already at the stage of graben formation (pull-apart versus half-graben). By the beginning of the plate stage, the Roslyatino asymmetrical graben with invariable polarity and Soligalich polygenetic sedimentary basin with the graben basement and the upper sag synform were already formed in the adjacent segments of the aulacogen (Figs. 7a, 7b).

Geological processes of the plate stage of the platform evolution led to the increase of differences in the segment structure. By the end of Vendian, the primary basin structures in both segments were disturbed by block movements of the basement with the highest amplitudes at the fault-bounded flanks (Fig. 7c, 7d). The strongest changes spanned preplate deposits of the Soligalich polygenetic basin: the symmetrical reversed morphostructure deciphered from the seismic survey data was already developed in general features.

At the later stages of the syneclise development, further deformations of the Soligalich and Roslyatino preplate complexes continued up to the Permian time, but their character remained unchanged. External forces led to the prograde deformation of the preplate complex and the increase of amplitude between its less subsided parts and bottom of troughs growing along the aulacogen (Figs. 7e–7h). By the end of Devonian, morphology of the reversed structures was completely determined and did not experience principal changes during the prograde subsidence of the region in the Carboniferous and Permian.

Assessment of Depths and Rates of the Subsidence of Aulacogen Segments at the Plate Stage

The modern asymmetrical structure of the syneclise was formed during the long-term and multistage subsidence at the plate stage of the platform evolution. This statement logically raises a question of the possible influence of aulacogen structures on the development of this asymmetry. Of special interest in this relation is the comparison of subsidence patterns between different segments of the aulacogen. Thicknesses of seismocompelxes taken to calculate the subsidence rate of separate segments are shown in Table 1.

These values were estimated with allowance for the seismic survey data, with preference given to the drilling data. The only exception is the Soligalich segment, where boreholes did not recover the Cambrian–Ordovician deposits. However, since seismic survey materials show the presence of these deposits on branches of the reversed structure, their average thickness was estimated as 50 m. Based on the accepted thicknesses, the depths of the top of the preplate seismocomplex by the end of great geological stages were determined (Table 2) and the plots of subsidence of four aulacogen segments were constructed (Fig. 8).

Analysis of the obtained data shows that the geological evolution of the Valdai–Molokovo segment sharply differs from that of other tectono-depositional parts of the aulacogen. At the plate stage of the platform evolution, this segment experienced uninter-

Table 2. Depths of the roof of the preplate complex at the end of great geological stages

Geological stages and time of their completion, Ma	Segments of aulacogen and depths of the roof of preplate complex, m			
	Valdai–Molokovo	Danilov–Lyubim	Soligalich	Roslyatino
R_3, 630	0	0	0	0
V_2, 542	−150	−680	−420	−250
Cm-O, 444	−650	−1210	−470	−250
S, 428	−700	−1210	−470	−250
D, 360	−1460	−2010	−1390	−880
C-P, 251	−1730	−2600	−2110	−1800
T-Q, 0	−1760	−2860	−2160	−1850

rupted prograde subsidence (Fig. 8). Unlike other segments, minimal (in depth and rate) descending movements occurred here in the Late Vendian time and from the Carboniferous to the Holocene. Within the time interval from the Cambrian to the terminal Devonian, the pattern of segment subsidence was similar to that of the Danilov–Lyubim segment. Although the Valdai–Molokovo segment was subsided to lesser depths, its section is most complete (in stratigraphy) and includes the Silurian deposits.

Segments located east of the Rybinsk fault are very similar in terms of the subsidence pattern. The main difference between them is ascribed to the Cambrian–Ordovician interval when intense subsidence occurred only within the Danilov–Lyubim segment. However, all segments show clearly expressed general regularity: the subsidence rates and depths in these segments increase with approaching to the Rybinsk fault.

DISCUSSION

Main conclusions based on the above presented data and additional considerations are as follows:

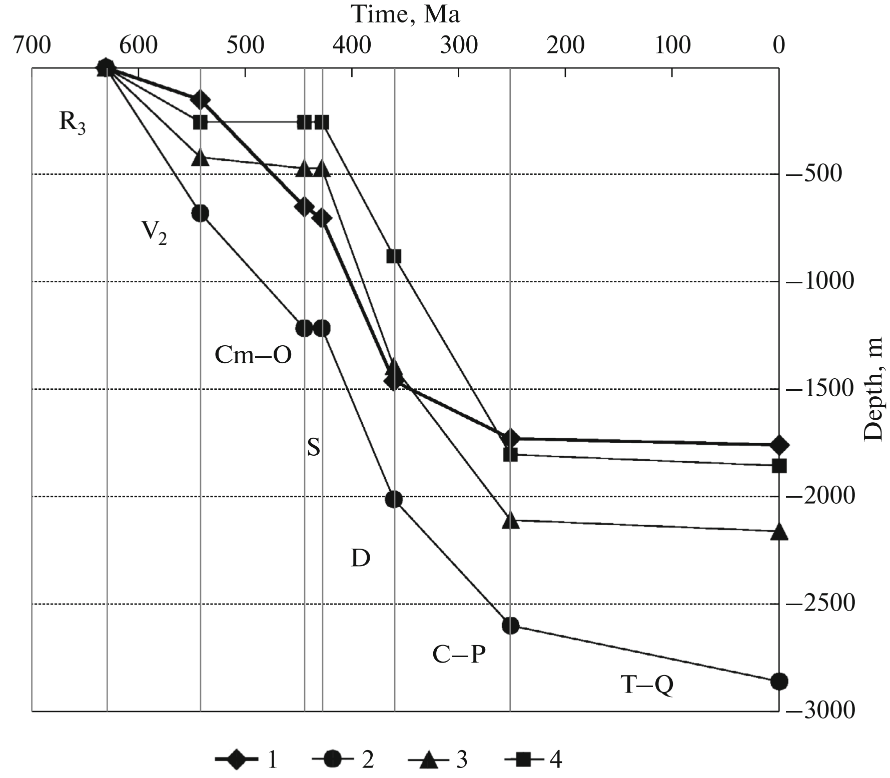

Fig. 8. Plots of the subsidence rate of aulacogen segments. (1–4) Segments: (1) Valdai–Molokovo, (2) Danilov–Lyubim, (3) Soligalich, (4) Roslyatino.

(1) Except the Valdai graben, all aulacogen structures are spatially confined to the sublatitudinal zone in the axial part of the Central Russian – Belomorian Belt. Deep normal falts serve as tectonic constraints for grabens of the Central Russian aulacogen.

(2) The preplate part of the section is reduced in the Danilov–Lyubim segment owing to uplifting of the basement blocks. This was caused by tectonic processes that affected the entire crust of the segment, which follows from the Moho uplift at the intersection of the Danilov–Lyubim segment and a band of the Rybinsk–Vologda deformations.

(3) The band of the Rybinsk–Vologda deformations is sharply discordant to the aulacogen strike. The Rybinsk fault is the most important structural boundary for all tectono-depositional elements of the Central Russian region in terms of some parameters. The fault provides transfer displacement of the axial line of aulacogen and the boundary of the sharply asymmetrical parts of syneclise. Plicative and reversed forms in the plate cover occur only east of this fault. Only eastern segments of the aulacogen show a systematic increase of the subsidence rate and depth at the plate stage with approaching to the Rybinsk fault, which is emphasized by inverse relationships of thickness of the Upper Vendian and Riphean deposits in the Danilov–Lyubim segment.

(4) The structure and composition of the preplate part of the sedimentary section can be described with the Upper Riphean Molokovo Group as example. Exception is the upper part of the Soligalich segment, which occupies a higher stratigraphic position relative to the upper red-colored sequence of the Molokovo Group.

(5) The lower parts of the Molokovo Group are made up of the basal detritus (few meters to tens of meters thick) facies and sufficiently thick (hundreds of meters) sediments of the deep lacustrine facies. Exception is the Danilov–Lyubim segment, which, in addition to the deep-water sediments typical of the lower parts of the group (Borehole Lyubim-3), contains the coarse poorly-sorted variegated deposits showing coarse cross-bedding, variations of bedding angles, and other features of tectonically unstable sedimentation environment recorded in boreholes in the Danilov area. Abundant influx of garnet, typical of the Vendian sedimentation, reflects an intense erosion of the garnet–biotite plagiogneisses in the segment basement. It is noteworthy that precisely these variegated deposits are correlated with the Obnorskaya and Kostroma formations, which compose the upper part of the preplate sequence in the Soligalich segment (Fig. 2).

Based on the above considered regularities of regional structure, relationships between the main lineaments of the belt of consolidated crust, structure of sedimentary sections, structural reconstructions, and estimated subsidence rate of local segments, let us consider the possible succession of tectonic and sedimentation events responsible for the formation of the modern structure and sedimentary cover of the Central Russian region.

Pre-aulacogen Stage

Reconstruction of the tectono-depositional history of the largest elements of the platform will be incomplete without consideration of the tectonic prehistory of their formation. An important event of this prehistory was the formation of the Central Russian–Belomorian Belt, the axial part of which accommodated the later aulacogen grabens and longitudinal axis of syneclise.

The above considered anomalous properties of consolidated crust of the belt are related to a series of tectonic and metamorphic processes that terminated in the Paleoproterozoic long before the aulacogen formation. According to some researchers, the Earth's crust beneath the future aulacogen experienced the influence of collisional events prior to extension (Aksenov, 1998; Bogdanova et al., 2008; *Glubinnoe ...*, 2010; Kostyuchenko and Solodilov, 1997; and others). The author of the present paper agrees with this concept and suggests the possible existence of a Paleoproterozoic collisional structure (crustal ridge) in the place of the future Central Russian aulacogen in the Neoproterozoic (Chamov, 2016a). Intracrustal melting in a thickened crust of the ridge led to migmatization of the tectonically juxtaposed heterogeneous complexes. Collapse of the ridge (1.75 Ga ago) caused the decompression melting and large-scale generation of granitoids. When granites/granodiorites (density approximately 2.9 g/cm^3) formed in the hypabyssal zone entered the higher-density environment, they tended to float isostatically to the upper crustal horizons. This process was facilitated by the intracrustal shearing, which always accompanies (or even initiates) the collapse of orogens. Floating and squeezing out of the granitized mass along shear zones (detachments) resulted in the formation of dynamometamorphosed rocks (blastomylonites) (Chamov, 2016a). Precisely the blastomylonite slices, which represent the petrophysically most contrasting and structurally weakened zones in the Earth's crust, played a significant role in the structural arrangement of the aulacogen in the Neoproterozoic.

Preplate Stage

The onset of large-scale destruction of the craton in the Late Riphean led to the initiation of extension structures, which were developed along the belt of granitized and dynamically reworked crust (Chamov, 2016a). The axial part of the belt initially related to the most migmatized region along the range axis underwent maximum dislocations during its collapse and became the most permeable corridor for the development of regional shear in the Neoproterozoic.

Coincidence of the graben development areas with ancient zones of the dynamic basement reworking is widespread in regions with the presence of large rift systems. For instance, the western branch of the East-African rift system is developed along crustal structures of several transcontinental Proterozoic shear zones (Ebinger, 1989; Ring, 1994). Organization of the resultant structures reflects the tendency of growing riftogen to develop by the minimization of mechanical efforts for deformation (Tevelev, 2002).

In the Central Russian region, secondary shear fractures (Riedel shears), which were developed simultaneously with the main shear zone, compensated stress in the strike-slip fault zone and determined the development of extension areas. With the development of en-echelon extension fractures oriented at an acute counterclockwise angle with respect to the axis of the sinistral strike-slip fault, structural parts of the grabens were formed along the general line of the aulacogen growth (Fig. 9a).

The structure of the local Neoproterozoic grabens (sedimentary basins) was determined by relationship between the planes of young (Neoproterozoic) fault planes and the inclination of Paleoproterozic blastomylonite slices of the basement: if the gentle slices are cut by normal faults, the basin depth seemed to be two times lower than if the fault plane coincided with the plane of steeply dipping slice (Chamov, 2015, 2016a). The character of these relationships is reflected both in the depths of newly formed basins and in the structure of sedimentary sections. Cross-cutting normal faulting, especially, in the case of gentle blastomylonite slices provided the formation of grabens with the rheologically defined limit of their structural depth: the subsidence of granitoid rocks into the denser amphibolite substrate was constrained by the isostatic leveling forces. Under the steady regional stress field, grabens of this type experienced lateral extension after attainment of the subsidence limit, which led to the accumulation of regressive sedimentary sequences with the irreversible transition from the lacustrine to the alluvial-proluvial sediments (Molokovo-type graben).

The development of grabens confined to normal faults along the steeply dipping blastomylonite slices is more favorable in terms of energy and resulted in the formation of narrow deep basins, where sedimentation environments did not virtually change with time. As shown above, the lacustrine sedimentation regime in the Roslyatino graben (deepest structure in the aulacogen) did not change in spite of any structural reorganization in the adjacent segments.

Immediately after the accumulation of thin near-fault sediments (“basal detritus”), the grabens evolved in the setting of relatively deep lakes and accumulated gray-colored sediments of the Molokovo Group (R_3^1), including the gray-colored part of the section of the Soligalich segment inferred in the undrilled area (Fig. 9b). Further development of the shoaling phase and/or tectonic movements led to the accumulation of variegated units (R_3^2). In the Molokovo-type basins, the further shear development led to the accumulation of red-colored sequence (R_3^3) of the Molokovo Group.

Transitional Stage

A complete change of tectonic settings from the preplate to plate stage of the platform evolution was preceded by some transitional period, which resulted in the local accumulation of specific sediments of seismocomplex (R_3^4), which rest on deposits of the Molokovo Group and underlie the plate seismocomplex V_2. Deposits of the Belarusian Group (seismocomplex R_3^4), which make up the Orsha Basin, are most widespread (Fig. 1). It was previously proposed that the Orsha Basin evolved as a depression that compensated significant horizontal displacements of blocks at the transitional stage (Chamov, 2016a, 2016b). It is reasonable to suggest that these events were responsible for the transfer displacement along the Rybinsk fault. Regardless of which part of the Earth’s crust – to the west or east of the transfer fault – experienced displacement with the amplitude of around 100 km, propagation path of the initially rectilinear regional shear faulting (wrench fault) came across the Archean solid Torzhok Massif, which could not but change the character of geological processes (Fig. 9c).

Regularities in the manifestation of compression and extension regions in relation with bending of the regional shear are considered in detail in (Cloos, 1928; Mann et al., 2007; Riedel, 1929; *Strike-slip deformation ...*, 1985; Tchalenko, 1970; Tevelev, 2005; Wilcox et al., 1973; and others). According to the general geological trends, the dextral displacement along the Rybinsk transfer fault and the appearance of a hard barrier on the propagation path of the Central Russian wrench fault should lead to the formation of intense compression region (contractional strike-slip duplex) accompanied by squeezing out of the crustal blocks and complete or partial erosion of the preplate complex (Figs. 9c, 9d). Since this area spatially coincides with the Danilov–Lyubim segment of the aulacogen, the most part of its preplate cover was eroded here. In addition, differentiated movements of the uplifted blocks were accompanied by the deposition of younger (relative to basal deposits) sediments that are interpreted correctly by V.A. Lapchenko in 1975 (see above). Exactly these youngest preplate deposits, which accumulated during the keyboard movements, should be considered as seismocomplex R_3^4 (Fig. 9d). These coarse proluvial variegated deposits rest both directly on the basement (boreholes Danilovskaya-4,

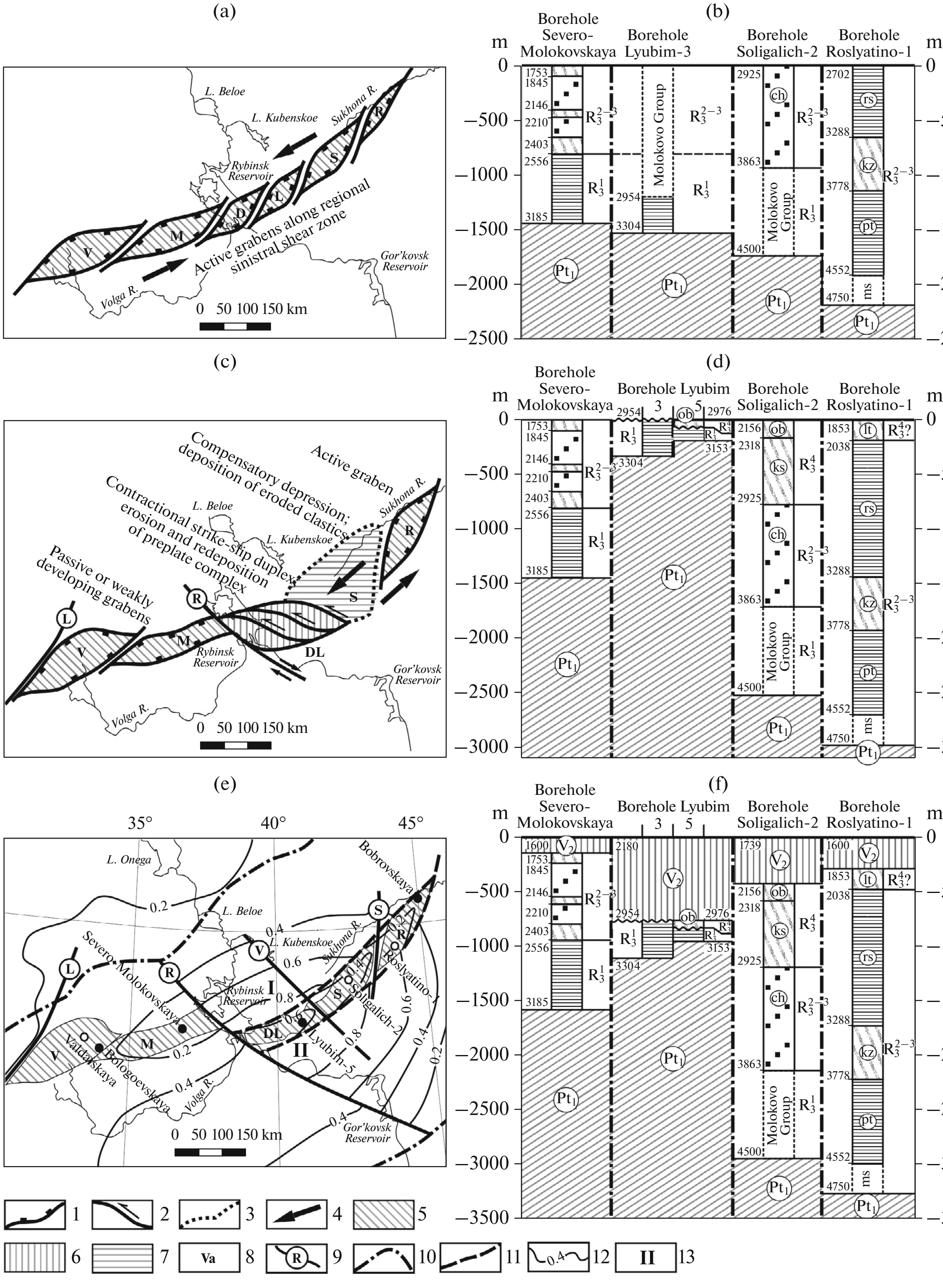

Fig. 9. Scheme of changes in tectonodepositional settings at different stages of the evolution of aulacogen and syneclise. (1) Downdip strike-slip fault; (2) updip strike-slip fault; (3) lithological boundaries of depressions: (4) regional strike-slip; (5–7) deposits: (5) aulacogen grabens, (6) relict and newly formed in the contractional strike-slip duplex; (7) newly formed in the compensatory sag; (8) grabens and segments of aulacogen—(V) Valdai, (M) Molokovo, (D) Danilov, (L) Lyubim, (DL) Danilov–Lyubim, (S) Soligalich, (R) Roslyatino; (9) regional faults; (L) Loknov, (R) Rybinsk, (V) Vologda, (S) Sukhona; (10) contour of syneclise; (11) activated plate complex at the end of Vendian; (12) stratohypses of the bottom of the plate complex at the end of Vendian; (13) secondary half-grabens of the downthrown block: (I) Gryazovets, (II) Galich. Other symbols are shown in Figs. 1, 2.

D'yakonovskaya-1) and on relicts of the deep-water lacustrine deposits (for instance, boreholes Lubim-4 and Lubim-5) (Figs. 2, 9d).

Exhumation of a great volume of tectonically mobilized material to the erosion area is accompanied by the appearance of suitable (for sedimentation) spaces, which compensate the compression and accumulate the eroded clastics (Kopp, 1997). The upper structural element (fields of a hat) of the Soligalich polygenetic sedimentary basin is ascribed to the family of such compensatory depressions, which lack any fault limitations but directly adjoin the erosion region. The compensatory depression is filled with the youngest preplate variegated sediments of seismocomplex R_3^4, which were redeposited from the Danilov–Lyubim erosion area: upper and middle units of the section (Obnorskaya and Kostroma formations) recovered by Borehole Soligalich-2 (Fig. 9d).

The Roslyatino graben at that time continued its evolution. However, its sequence is not correlated with the surrounding sedimentary complexes, indicating the isolation of its depocenter from the clastic material delivered from the Danilov–Lyubim Uplift.

The development of grabens of the Valdai–Molokovo segment was presumably terminated owing to compensation of the regional shear faulting by the Rybinsk–Vologda (Danilov–Lyubim) contractional strike-slip duplex.

Plate Stage

By the beginning of the Late Vendian, intense tectonic processes of the transitional stage were completed. Compression and horizontal redistribution of masses gave way to the subsidence of spacious territories. Extinction of the regional sinistral strike-slip faulting in combination with the general extension caused relaxation of the compression area in the Danilov–Lyubim segment with the subsequent formation of a large subregional normal fault (downdip strike-slip fault) along the Rybinsk fault. Subsidence of the faulted block to the east of the fault led to the initiation of the single Gryazovets–Galich asymmetrical half-graben (Fig. 9e). The half-graben had the maximum depth near the central part of the Rybinsk normal fault and gradually became shallower both along its northwestward and southeastward flanks and along the northeastward updip of the faulted block. The subsidence depth of separate segments corresponds to thickness of the Upper Vendian deposits, which rapidly increases toward the Rybinsk fault. It should be noted that thickness of the Upper Vendian deposits above the Valdai graben in Borehole Valdai (around 300 m) is twice as high as that of the Upper Vendian deposits above the Molokovo graben. Such difference in the subsidence value can be related to proximity of the Molokovo graben to the Rybinsk fault as a result of the isostatic "floating" of footwall margin after the formation of the normal fault.

The prograde development of the Gryazovets–Galich half-graben was accompanied by the stepped subsidence of segments. Based on estimates of the subsidence, its intensity increased toward the Rybinsk normal fault (Fig. 9f). Correspondingly, the deepest subsidence took place in the Danilov–Lyubim segment. The subsidence depth of the crust systematically decreases to northeast of the Rybinsk fault. This is reflected in the structure of the Soligalich and Roslyatino segments. This tendency was typical during the entire time of syneclise formation and best expressed at the early subsidence stages. In particular, it is reflected in the gradual pinchout of the Cambrian and Ordovician deposits toward the Roslyatino segment (Figs. 4–6).

The hypsometric position of any crustal block is determined by the isostatic law (*Tolkovyi* ..., 2002). The rock density has a decisive significance. Under otherwise equal conditions, the lighter rocks acquire excessive floating capacity with respect to the surrounding rocks. For this reason, the tectonized and granitized aulacogen segment with abundant sedimentary deposits and density less than 2.9 g/cm^3 were forced to subside less rapidly than other parts of the faulted block of the growing half-graben. Delay of the aulacogen segment subsidence (relative to amphibolite rocks with density over 3.0 g/cm^3) caused the gradual development of reversed structures in the plate cover. Such noninversion (without change of sign toward tectonic movements) mechanism of cover deformation well explains the absence of reversed structural forms to the west of the Rybinsk fault.

At the same time, in spite of the absence of clear evidence, we cannot exclude the existence of self-oscillating movements caused by the isostatically excessive subsidence of aulacogen segments during the subsequent normal faulting and floating of the overdeepened segments of the aulacogen at an equilibrium depth. In this case, we can speak about inversion periods, when the direction of tectonic movement was changed into the opposite one and the normal faults were activated as reversed faults to reach the isostatic equilibrium. In other respects, the Molokovo horst (normal fault transformed into reversed fault) is the only inversion structure within the aulacogen.

The decisive factor in the formation of the modern structure of the syneclise was the orthogonal (with respect to the Rybinsk fault) position of the chain of aulacogen structures. Prograde subsidence was accompanied by increase of the isostatic disequilibrium of crustal elements, resulting in separation of the initially single half-graben into two structures of different vergency: Gryazovets and Galich troughs (secondary half-grabens). Boundary faults of aulacogen segments lagging in subsidence served as the main normal faults for the new structures.

During further subsidence of the syneclise, the tectono-depositional system tended to reach and maintain the isostatic equilibrium between segments of the anomalous granitized crust with enclaves of the preplate sedimentary cover (local heterogeneity) and denser amphibolite framework. This scenario describes logically the formation of the most subsided part of syneclise in the modern structure.

CONCLUSIONS

Analysis of the structural plan of the region and sedimentary cover structure allowed us to reconstruct the sequence of the main stages of region evolution and trace the main regularities of their realization and evolutionary inheritance.

The position of the aulacogen and, later, syneclise was predetermined long before the beginning of riftogenic processes in the Neoproterozoic. The preceding migmatization and decompressional dynamometamorphism during collapse of the collisional range in the Paleoproterozoic led to the formation of the Central Russian–Belomorian Belt consisting of relatively light and permeable crust that was favorable for the development of regional strike-slip faulting.

Initiation of aulacogen grabens at the preplate stage was related to the regional shearing. Change of structural plan of the territory in the transitional period caused the transfer displacement of the initially rectilinear regional strike-slip faulting and the appearance of a rigid Archean massif on the way of its propagation, resulting in the development of contractional strike-slip duplex, squeezing out of some basement blocks, and exhumation of a significant part of deposits of the preplate cover to the erosion area. The eroded material was redeposited in the compensatory depression adjacent to the erosion salient. At the plate stage, the transcrustal transfer disturbance played a great role in the formation of the structural plan of the growing syneclise. Relaxation regime in the platform led to initiation of a large normal fault, which was sharply discordant to the aulacogen axis. Prograde subsidence of the faulted limb (Gryazovetsk–Galich half-graben) was complicated by the presence of orthogonal (relative to the normal fault) lithotectonic heterogeneity (chain of aulacogen segments). The lower (relative to the surrounding frame) subsidence rate of these comparatively light fragments of the aulacogen crust led to the appearance of reversed forms in the plate cover.

Thus, the modern structure of the sedimentary cover of the Central Russian region is the result of tight interaction of tectonic and sedimentary processes in the upper crust and sedimentary cover. Although the driving mechanisms changed cardinally at different stages of the platform evolution, the area of their manifestation remained unchanged during the long-term (hundreds of million years) period of geological time. Petrophysical properties of the Paleoproterozoic crust predetermined the region of riftogenic processes in the Neoproterozoic. The development of regional strike-slip faulting controlled the development of the aulacogen, while the appearance of transfer displacement of its axis predetermined the structural asymmetry of syneclise. Thus, the Central Russian region can be considered as a single long-lived polygenetic tectono-depositional system.

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