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The Borschovo section of the Gauja and Amata regional stages (Leningrad Region, Russia): sedimentology and biostratigraphy

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Abstract. The results of the detailed sedimentological study and bed-by-bed collecting of fossils from the Borschovo section exposing the upper Givetian–lower Frasnian boundary beds are discussed. The succession consists of sandstones alternating with argillaceous and clayey packages that contain vertebrate and plant remains in the upper part. The grain size, sedimentary structures and cross-bed orientation considerably differ in the Oredezh Beds and the Staritsa Beds. Fine- to coarse-grained cross-stratified sandstones of the Oredezh Beds most probably are fluvial deposits, whereas the sandstones of the Staritsa Beds yielding tidal structures that show variable directions of the cross-bedding were accumulated in a tidally influenced or even tidally dominated environment. The Oredezh Beds in the study area lack fossils; however, sedimentary features allow correlation with the Sietiņi Formation corresponding to the lower part of the Gauja Regional Stage. The age of the Staritsa Beds is defined based on the distribution of vertebrate taxa as corresponding to the Amata Regional Stage. Probably, the deposits from the Borschovo locality represent the most complete section of the Staritsa Beds, including its lowermost part. Rather good preservation of some thin and fragile fish bones, buried together with large-sized quartz grains, and wide taxonomical diversity, are characteristic of the Borschovo locality, which is not common for the vertebrate localities of the Main Devonian Field corresponding to the Amata Regional Stage.

Key words: Middle–Upper Devonian, siliciclastic deposits, sedimentary environment, vertebrate assemblage.

INTRODUCTION

Boundary intervals of chronostratigraphic units are always significant for correlation purposes, and the Middle–Upper Devonian boundary is no exception. Devonian deposits are widely distributed in the Baltic countries and northwestern part of Russia, cropping out in a relatively narrow belt, known as the Main Devonian Field (MDF), in the northwestern part of the East European Platform, along the southern margin of the Baltic Shield. This area of exposed Devonian deposits consists of two parts most probably separated during the post-Visean denudation: the western part stretches through Estonia, Latvia, Lithuania and the northern part of Belarus, including part of the Baltic Sea floor, and the eastern part corresponds to the territory of the Leningrad, Pskov, Novgorod and Vologda regions of northwestern Russia. The western part of the MDF is also known as the Devonian Baltic Basin (Pontén & Plink-Björklund 2009) or the Baltic Devonian Basin (Lukševičs et al. 2012).

The territory of the MDF in Devonian time developed as a shallow epicontinental sea, often with restricted connection to open ocean. This setting determined the peculiarities of the living habitats and burial environments of Devonian organisms. The level of the World Ocean and biodiversity, including vertebrates (Lebedev et al. 2010; Lukševičs et al. 2010), changed dramatically, and in the MDF the mostly clastic sedimentation model close to the Givetian–Frasnian boundary was replaced by the predominantly carbonate sedimentation and mixed model (Kuršs 1975) associated with rather drastic replacement of the dominant facies and their associations. In contrast to the deposits of the open shelf, vertebrate and spore fossils dominate the deposits of the MDF close to the Givetian–Frasnian boundary. The stratigraphically valuable invertebrates, ammonoids, are missing in those deposits, and conodonts are very rare, being represented by a shallow-water polygnathid assemblage. It makes the precise correlation with stratotypical sections and even sections from neighbouring areas of the East European Platform more difficult (Esin et al. 2000). Spores have not yet been found in the deposits of the Burtnieki to Gauja regional stages (RSs) in the eastern part of the MDF, and only vertebrates can be used in stratigraphic correlations. Therefore a detailed sedimentological study and facies analysis are needed to determine changes in the sedimentary environment in time, which can be an important marker in stratigraphy.

The most representative sections of the Givetian–Frasnian boundary interval in the eastern part of the MDF are located in the Luga River Basin, Leningrad Region, Russia. Detailed studies of the Devonian deposits in this area started in 1926–1931 during the geological mapping organized by the Main Geological Prospecting Trust (Ivanov & Lebedev 2011). Two groups of geologists, supervised by Boris Asatkin and Roman Hecker, described in detail series of outcrops and boreholes and gathered large collections of fossils. The fossils were carefully documented and related to definite intervals of the section, demonstrating bed-by-bed distribution of taxa. Dmitry Obruchev who worked in cooperation with Hecker had also done considerable work distinguishing several fossil-rich beds. Contrariwise, most authors of later publications usually provide only lists of taxa or characteristics of faunal assemblages of various stratigraphic units, often regional stages, while the bed-by-bed distribution of taxa is documented in definite sections in only few cases.

The section of the Devonian deposits at the Borschovo Village near the Oredezh River has been known since works of Dmitry Obruchev (Obruchev 1933). The Borschovo section and nearby mines are defined as a Regional protected geological monument. In 2001 a team of the Latvian–Russian expedition (Alexander Ivanov, Ervīns Lukševičs, Ģirts Stinkulis, Kristīne Tovmasjana, Ivars Zupiņš and Pavel Beznosov) initiated new studies of the Devonian vertebrates from the Borschovo section, where sandstone intercalated by clay and mudstone crops out (Ivanov et al. 2011). Later, in 2009 and 2010, the team of the Russian–French–Latvian expedition, as well as in 2011 the group of participants in the D. Obruchev Symposium during the field excursion, collected an abundant material of vertebrate remains there.

The Devonian section near the Borschovo Village is rather well exposed in several outcrops and of considerable thickness, which allows analysis of sedimentary environment and its changes, as well as comparison with other sections in the northwestern part of Russia and the Baltic States. However, sedimentological studies in this object were not performed until 2012.

GEOLOGICAL SETTING AND STRATIGRAPHIC SUBDIVISION

The deposits corresponding to various Middle and Upper Devonian stratigraphic units are exposed in several picturesque outcrops along the Oredezh River, the right bank tributary of the Luga River, Luga District, Leningrad Region (Fig. 1). The deposits belonging to the Oredezh Beds and the Staritsa Beds are found in a 20 m wide and 10 m high exposure on a terrace at the left bank of the Oredezh River, in an extended, overflow area of this river called Lake Antonovo. The exposure studied lies to the right of the road from the Borschovo Village, approximately 32 km NEE from the Town of Luga. The Staritsa Beds have been described in the Devonian section in this area (Rukhin 1946). Based on a very characteristic vertebrate assemblage, documented in several outcrops in the vicinity of the well-known Yam-Tesovo locality, in the current stratigraphic chart they correspond to the lower part of the Amata Regional Stage (RS) (see e.g. Hecker et al. 1935; Karatajūte-Talimaa 1963; Obruchev & Mark-Kurik 1965).

The deposits of the Staritsa Beds, represented by yellowish sandstones with interlayers of siltstones and clays, are exposed in the Borschovo outcrop. Slightly more than 100 m to the northwest of this object, in several artificial caves directly on the left bank of the Oredezh River, white sandstones of a slightly older interval of the Devonian were documented. They underlie the sandstones of the lower part of the Staritsa Beds and likely belong to the upper part of the Oredezh Beds. These artificial caves (mines) were prospected and raised in 1927–1929. The contact of both beds is well represented in the caves.

At least four versions of the position of the Middle and Upper Devonian boundary in the geological section of the MDF have been proposed: between the Burtnieki and Gauja RSs; between the Gauja and Amata RSs; within the Amata RS, at the base of the Podsnetogorskie Beds; and at the base of the Snetnaya Gora Beds of the Pļaviņas RS (for detailed discussion see Esin et al. 2000; Mark-Kurik & Põldvere 2012). In recent studies the base of the Amata RS is usually accepted as the position of this boundary: the deposits corresponding to the Amata RS (Amata Formation (Fm.) in Latvia and Estonia; upper part of the Šventoji Fm. in Lithuania; Zhelon RS in Belarus; the Staritsa Beds and the Podsnetogorskie Beds in NW Russia); or at least their

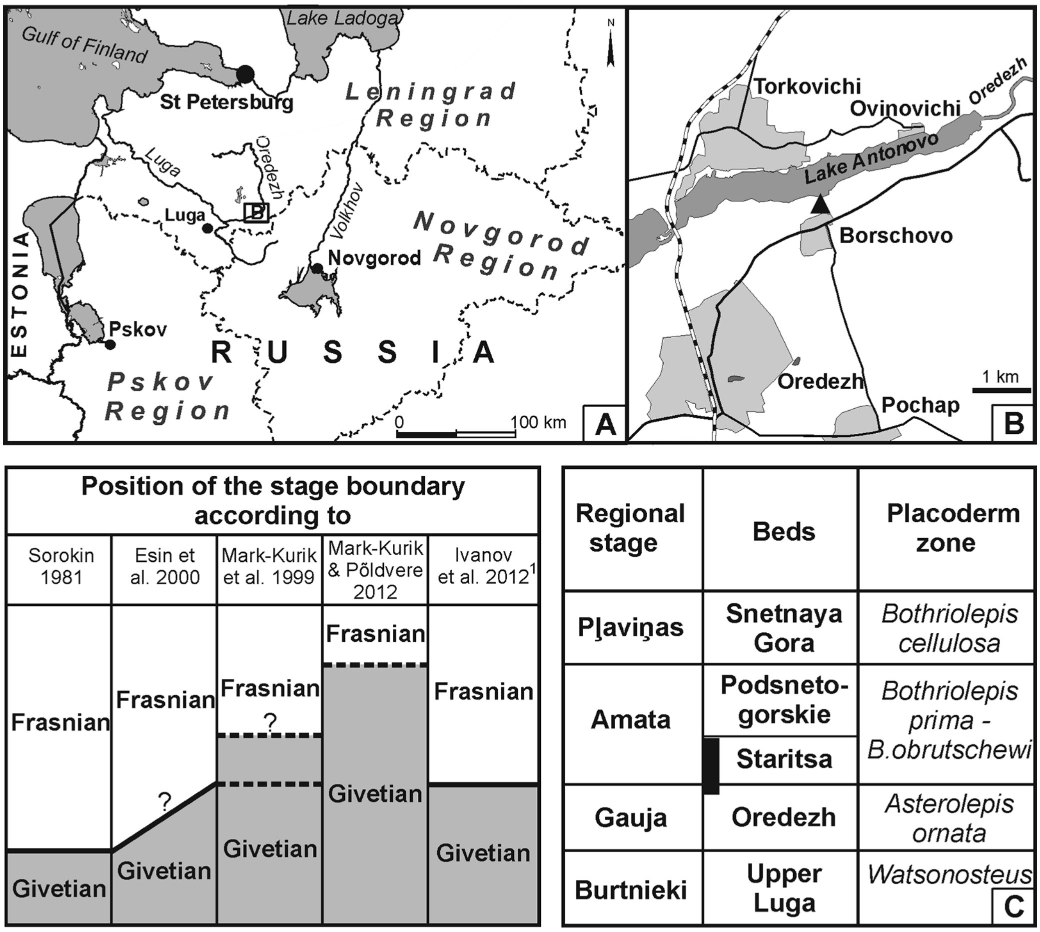

Fig. 1. A, **B**, locality maps of the Borschovo outcrops (black triangle). **C**, the position of the Givetian–Frasnian boundary according to various authors;[1], the same position is also accepted by Glinskiy & Mark-Kurik 2016, Lukševičs et al. 2012 and in this article.

upper part, most commonly have been treated as the earliest Late Devonian in age (Mark-Kurik et al. 1999; Esin et al. 2000; Ivanov & Lebedev 2011; Ivanov et al. 2012; Lukševičs et al. 2012; Mark-Kurik & Põldvere 2012; Glinskiy & Mark-Kurik 2016). In this study the Amata RS is allocated within the Frasnian Stage.

MATERIAL AND METHODS

In the summer of 2012 detailed logging of the Devonian succession was carried out for the easternmost outcrop No. 3 (Staritsa Beds) and two small outcrops in its vicinity (contact zone of the Oredezh and Staritsa beds) by D. Tirzmale and Ģ. Stinkulis (Fig. 2). Measurements of cross-stratification, in total 58, were done to determine the direction of palaeotransport and to study bedform morphology. Vertebrate remains were gathered by the team of the Russian–French–Latvian expedition (including the author of this paper, A. I.) during the field seasons of 2009 and 2010, during the field excursion of participants in the D. Obruchev Symposium (including A. I. and E. L.) in August 2011, as well as by Alexander Ivanov, Ervīns Lukševičs and Vadim Glinskiy in the spring and summer of 2012. The obtained collection of vertebrates is kept in the Paleontological Museum of St Petersburg State University.

RESULTS

Sedimentology

The oldest Devonian deposits exposed in the vicinity of the Borschovo Village are siliciclastic ones, such as white sandstones with trough cross-stratification and clay clasts. However, no visible features indicative of tidal processes were observed, like mud drapes on cross strata, reactivation surfaces, climbing ripples on cross

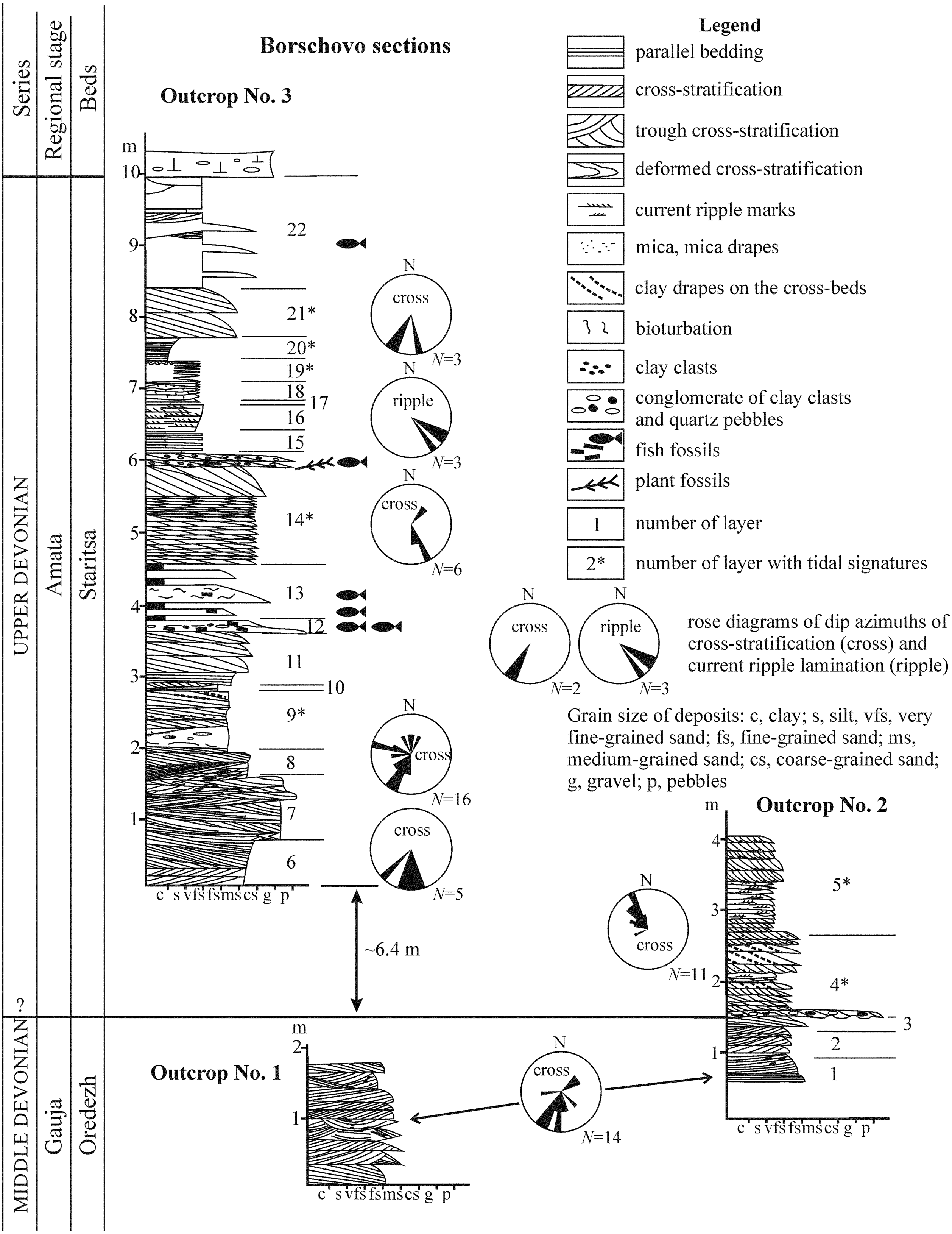

Fig. 2. Section of the Devonian deposits near the Borschovo Village at the left bank of the Oredezh River, Luga District, Leningrad Region, Russia. *N*, number of measurements.

strata, etc. Trough cross-stratification gives evidence of the accumulation of the sandy material in migrating lingoid (lunate) subaqueous dunes subjected to traction currents (Reineck & Singh 1980; Nichols 1999; Pontén & Plink-Björklund 2007). Textures and structures of deposits, as well as the lack of features indicative of tidal processes, suggest the accumulation of the material in the fluvially-dominated environment. The cross-strata dip shows the palaeocurrent direction mostly to 200–240° (SW), but the direction to the NE is evident too, and some azimuth measurements indicate westerly and southeasterly oriented currents. These sandstones in outcrops 1 and 2 lack any fossils.

The distinct and peculiar boundary between the white sandstones (Oredezh Beds) and overlying reddish and yellowish sandstones (Amata RS, Staritsa Beds) is exposed in the caves at the left bank of Lake Antonovo (outcrop No. 2). The proposed age of the deposits is discussed further.

In most places the boundary coincides with the erosional surface, often covered by a conglomerate that is composed of up to 30 cm large clay clasts (Fig. 3A, B). This surface suggests considerable erosion of sandy deposits of the Oredezh Beds at the beginning of Amata time when the Staritsa Beds accumulated.

In several places the boundary of white and reddish sandstones forms peculiar ‘pockets’ with steep walls. Such structures are not typical for current erosion processes and could rather be interpreted as formed by water-escape or displacement of sediments. This well-

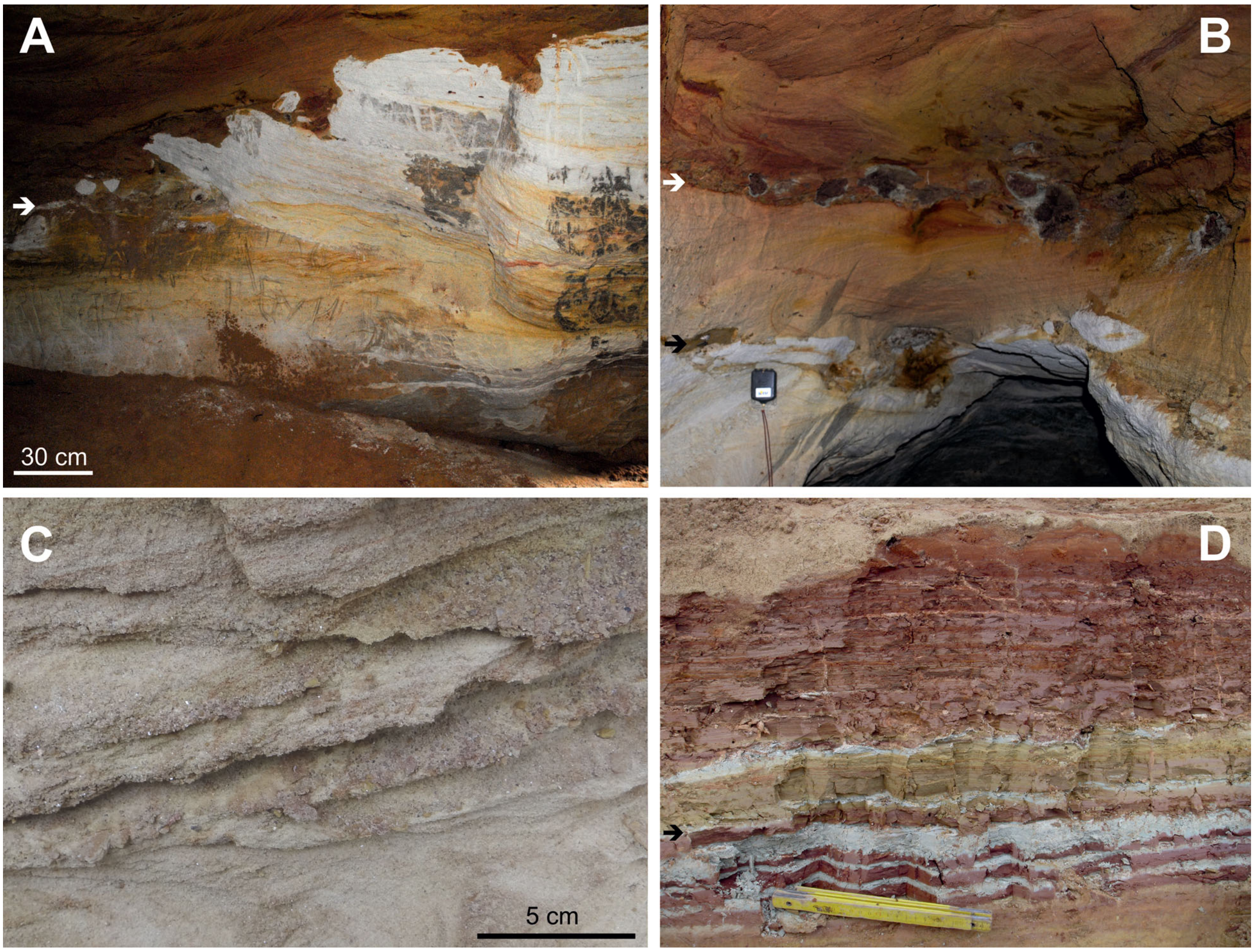

Fig. 3. The Devonian deposits from the Borschovo locality. **A**, irregular contact (white arrow) with peculiar pockets between the white sandstones of the Oredezh Regional Beds and the red sandstones of the Staritsa Regional Beds in an artificial cave, outcrop No. 2. In some places clasts of white sandstones are redeposited in red sandy material. This contact corresponds to the boundary of layers 3 and 4. **B**, the same contact at the same site (black arrow) and another erosional surface 40 cm above it (white arrow) marked with clay clasts. The length of the geological compass is 10 cm. **C**, sandstone with gravel-size quartz grains, outcrop No. 3, the upper part of layer 14. **D**, tidal rhythmites of layers 19 and 20. The contact between the layers is marked by a black arrow. The length of the ruler is 22 cm. For numbers of outcrops and layers see Fig. 2.

expressed erosional surface between two units of regional stage-scale could be interpreted as a sequence boundary (Catuneanu 2006).

The lower part of the Staritsa Beds, 2.5 m thick, is also exposed in the caves. The deposits are very fine to medium-grained sandstones with trough-stratification of small thickness (5–20 cm). Very fine-grained sandstones with current ripple-lamination are present in one 60 cm thick interval 1 m above the base of these beds.

As revealed by approximate levelling using the geological compass, the base of the Devonian deposits in the Borschovo outcrop No. 3 is on a higher hypsometrical level than the boundary of the Oredezh and Staritsa beds in the cave closest to the outcrop. The height difference is 6.4 m, but the possible influence of the inclination of bed surfaces is not taken into account. It means that a 4 m thick part of the Staritsa Beds is not available for documentation, and its composition is not known.

In the easternmost outcrop (No. 3) the lower part of the section of the Staritsa Beds (layers 6–11) is composed of reddish, cross-stratified sandstones similar to those in the caves. These fine-grained to gravelly sandstones, 3.7 m thick, are dominated by trough cross-stratification structure, which indicates the transport and sedimentation of sand material in the lingoid subaqueous dunes, under the influence of traction currents. Sandstones in several intervals contain quartz pebbles, up to 3 cm large, and clay clasts, which give evidence of high current velocity. These sandstones lack clear clay or mica drapes on the cross-laminae, tidal bundles, reactivation surfaces and any other structures evidencing tidal processes. Only in the interval 2.7 m above the base of this bed, clay drapes occur on the cross-strata, which probably indicate some tidal influence on sedimentation.

Sandstone with the clay clasts and quartz pebbles (layer 12, 20 cm thick) are associated with diverse and well-preserved, but usually disarticulated vertebrate remains (Fig. 4B). This is the richest vertebrate fossil-bearing bed in the Borschovo outcrop. The vertebrate-rich bed is covered by layer 13, which is 0.6 m thick and represented by the alternation of coarse-grained to gravelly sandstones and clays.

Upwards, there occurs a 1.45 m thick interval of fine- to coarse-grained sandstone (layer 14). Trough cross-beds of small thickness (2–10 cm) dominate. Only one cross-bed reaches a thickness of 40 cm, which also contains reactivation surfaces. This part is covered by a 10 cm thick layer of conglomerate (the upper part of layer 14), composed of clay clasts, quartz pebbles and gravel, containing very fragile and fragmented vertebrate remains (Figs 3C, 4A, C) and macrofossils of plants. The matrix of this conglomerate is composed of fine- to medium-grained sand.

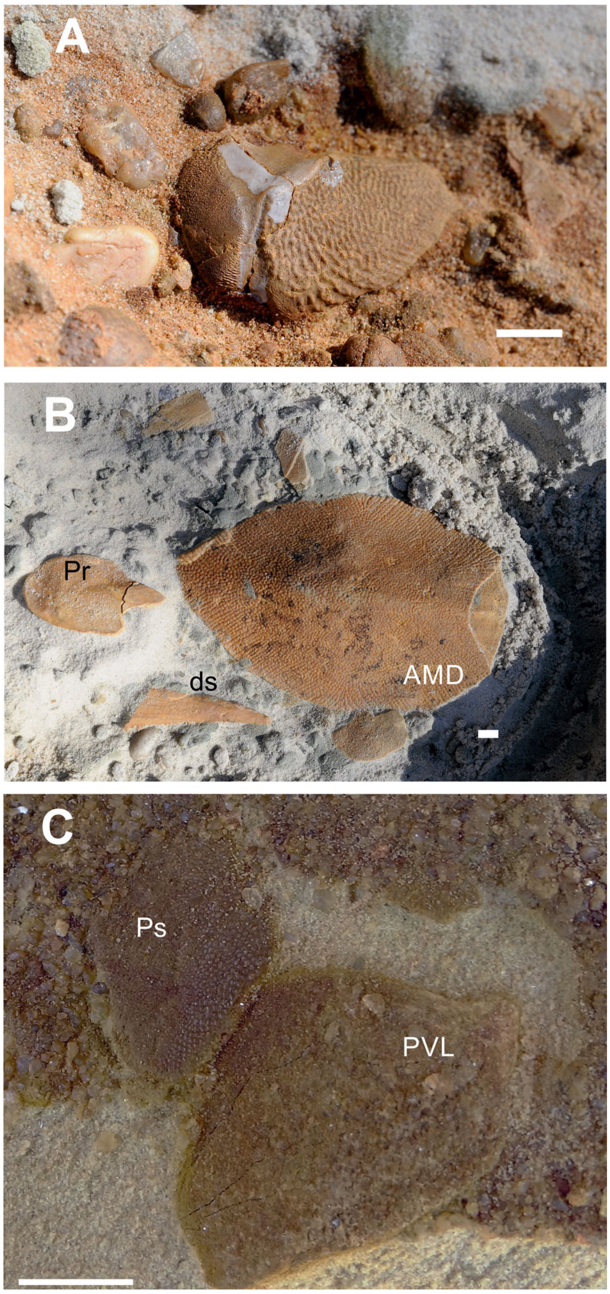

Fig. 4. Vertebrate fossils in the Devonian sandstone from the Borschovo locality. **A**, *Asterolepis radiata* Rohon, right ventral central plate 1 in sandstone with pebble-size quartz grains, the upper part of layer 14. **B**, *A. radiata*, anterior median dorsal plate (AMD) and the distal segment of the pectoral fin (ds), fragment of porolepiform fish (Pr) and other fossils in the sandstone with pebble-size quartz grains of layer 12. **C**, partial branchial plate of *Psammosteus* sp. (Ps), fragmentary posterior ventro-lateral plate of *A. radiata* (PVL) and other fossils in the sandstone with gravel-size quartz grains of layer 14. A, B, courtesy of Vachik Hairapetian (Islamic Azad University Isfahan, Iran); C, courtesy of Vadim Glinskiy (St Petersburg State University, Russia). Scale bars 1 cm.

The conglomerate is overlain by a 1.70 cm thick bed (layers 15–20), represented by the alternation of various, mostly finely laminated deposits consisting of (1) alternating thin layers of very fine-grained sandstone and siltstone that intermix with thin clay layers, (2) very fine-grained sandstone with current ripple-lamination, (3) silty sandstone with very fine wavy and lenticular lamination and (4) very fine laminated siltstone with admixture of clay (Fig. 3D). Rhythmic bedding and alternations, as well as wavy and lenticular bedding structures indicate the action of tidal processes (Reineck & Singh 1980).

The upper part of the Devonian section is represented by cross-stratified, medium- to fine-grained sandstone (two cross-beds), 0.7 m thick in total (layer 21), which is topped by a 1.5 m thick sandstone bed (layer 22). The latter is deformed and likely influenced by Pleistocene glacial and/or glaciofluvial processes. The topmost, deformed sandstone bed contains Devonian vertebrate remains, as well as articulate brachiopods and crinoids most probably of Ordovician age. Presumably, part of this material was mixed with the Devonian sandstone matrix during the Pleistocene glaciations.

Vertebrate assemblage: taxonomic composition and some remarks on taphonomy

Vertebrate remains occur in four layers of the Staritsa Beds that are exposed in outcrop No. 3 of the Borschovo locality. The lowermost vertebrate-bearing layer (layers 7 and 8) yields rare isolated skeletal elements of the psammosteid *Psammolepis* sp., arthrodire *Plourdosteus livonicus* (Eastman), antiarch *Asterolepis* sp., acanthodian *Haplacanthus* sp., an unidentifiable dipnoan fish, as well as porolepiforms *Glyptolepis* sp. and Porolepiformes gen. indet. The vertebrate assemblage was most diverse in layer 12, containing well-preserved abundant plates of the psammosteids *Psammolepis undulata* (Agassiz), *Psammolepis venyukovi* Obruchev, *Psammosteus livonicus* Obruchev, *Psammosteus praecursor* Obruchev, antiarch *Asterolepis radiata* Rohon and arthrodire *Eastmanosteus* cf. *pustulosus* (Eastman), as well as rare scales and bones of the porolepiform fish cf. *Glyptolepis* sp. (Fig. 4B). Layer 13 produced rare remains of *Psammolepis venyukovi*, *Psammosteus livonicus, Ps. praecursor*, *Asterolepis radiata* and *Eastmanosteus* cf. *pustulosus*. The topmost conglomerate of layer 14 contains fragmented vertebrate remains of *Psammolepis* sp., *Asterolepis* sp. and an unidentifiable porolepiform fish (Fig. 4A, C). The topmost layer (No. 22) contains the remains of *Psammosteus* sp., *Asterolepis* sp., *Bothriolepis obrutschewi* Gross and ?*Eusthenopteron* sp.

The composition of the assemblage from this part of the section is rather typical for the Old Red Sandstone facies *s.l.* Psammosteid heterostracans (Pteraspidomorpha) predominate in number among species-level taxa, but the specimens of antiarch placoderm remains are most numerous. Psammosteids are represented mainly by branchial plates whereas the other skeletal elements (fragments of central plates, ridge scales and tesserae) are very rare. The placoderm fish *Asterolepis radiata* is represented by almost all skeletal elements of the dermal armour, which are mostly disarticulated, except for several articulated distal segments of the pectoral fin, and one specimen consisting of articulated nuchal and postpineal plates. Still, it is difficult to explain the rather good preservation of some skeletal elements, including such thin and fragile bones as sclerotical or terminal plates, buried together with large quartz grains.

The dermal plates of the other placoderm fishes, *Plourdosteus livonicus* and *Eastmanosteus* cf. *pustulosus*, the scales and bones of the head and shoulder girdle, as well as isolated teeth of porolepiform sarcopterygian fishes including *Glyptolepis* sp., occur only rarely. The remains of the acanthodian *Haplacanthus* sp., tristichopterid ?*Eusthenopteron* sp. and an unidentified dipnoan fish, are extremely rare and usually rather fragmentary. Many plates of psammosteids and the antiarch *Asterolepis* bear traces of pathology, such as bite marks, hollow swellings, oval or round fossulae or an abnormal crest on the external surface of plates that are most probably caused by parasites (Lukševičs et al. 2009) or bone diseases. In many cases the surface of the bones is covered by deep impressions of sand grains. Two main reasons could be responsible for these marks: chemical weathering or trampling by relatively coarse sand grains under the weight of quickly accumulated sand and gravel.

The assemblage from the uppermost layer of the Devonian deposits in the Borschovo locality, consisting of *Psammosteus* sp., *Asterolepis* sp., *Bothriolepis obrutschewi* and ?*Eusthenopteron* sp., differs from older assemblages not only in its composition, but also in the state of preservation. The remains is that assemblage are smaller, less abraded and of slightly darker colour.

DISCUSSION

Sedimentary environments

All studied Devonian deposits in the Borschovo site are siliciclastic sedimentary rocks. However, their grain-size, sedimentary structures and cross-bed orientation considerably differ between the Oredezh Beds and the Staritsa Beds.

Deposits of the Oredezh Beds in the Borschovo outcrop and neighbouring areas are fine- to coarse-grained sandstones. Varigrained, often coarse-grained textures of deposits, their sedimentary structures indicating the development of erosional surfaces and channels, lingoid subaqueous dunes and bars, the dominant current direction and channel orientation to the south, southeast and southwest, as well as the absence of tidal features (e.g. mud and mica drapes, tidal bundles, reactivation surfaces) allow their interpretation as fluvial deposits.

Tidal features are present in at least four layers in various parts of the succession of the Staritsa Beds in the Borschovo outcrop, with the exception of its lower part. Sandstones yield clay and mica drapes on the cross-beds, graded lamination on the cross-beds and rhythmically changing tidal bundles, which indicate periodic variation in the tide amplitude (Nichols 1999). Reactivation surfaces, evidencing a changing direction of flood and ebb current, and wavy and lenticular bedding, indicating periodic changes in water agitation during tides (Reineck & Singh 1980), are also present in the studied succession. Rhythmic alternation of sandy and clayey to silty deposits, as well as parallel laminated clayey deposits, most possibly are tidal rhythmites formed due to periodically varying water level and agitation during tidal processes (Reineck & Singh 1980).

Sandstones of the Staritsa Beds show various cross-bed dip azimuths, mainly to the NNW, WNW and SSW. Several other directions are noted as well, except for the NE, E and SE. Different directions of the cross-bedding may indicate both the development of the slopes of the bedforms in various orientations and changing directions of tidal currents.

Sedimentological data in one exposure were not sufficient for interpreting facies and their assemblages. No convincing vertical trends in textural or structural changes of deposits were noted either. We suggest that the deposits of the Staritsa Beds exposed in the Borschovo site were accumulated in a fluvial environment under considerable influence of tidal processes. Tidally dominated environment could not be excluded as well, however, due to scarce occurrence and small size of outcrops, the possibility of evaluating the role of tidal currents in the formation of the observed bedforms is limited. Because of insufficient sedimentological data from the study site and its neighbouring objects, it is necessary to summarize the results of the sedimentological studies and palaeogeographic reconstructions from the widely studied central, northwestern and western parts of the Baltic Devonian Basin. These parts of the basin are located 300–500 km westwards from the studied site.

V. Kuršs conducted wide-scale sedimentological and mineralogical investigations (Kuršs 1975, 1992). He provided palaeogeographic reconstructions, suggesting that the deposits of the Gauja RS were formed in a southerly prograding deltaic zone (northeastern part of the basin) and a shallow sea (the rest of the basin). Both the Sietiņi Fm. and the Lode Fm. (respectively the lower and the upper part of the Gauja RS in Latvia) in the northeastern part of the basin, including our study area, were interpreted to be formed on the submarine slope of the delta.

According to the results of recent studies of Pontén & Plink-Björklund (2007, 2009), sediments were deposited in a tide-influenced delta environment during Gauja time. Data from the deposits of the Sietiņi Fm. in the Bāle sand pit (sectors 1 and 2) confirm the development of the delta plain during the beginning of the deposition of the Gauja RS, as suggested by Pontén & Plink-Björklund (2007, 2009). However, the influence of tidal processes on the sedimentation regime in this time seems to be insignificant (Blāķe et al. 2013). Thus, several authors suggest that the accumulation of sandy deposits in a fluvially dominated, prograding delta is the most possible sedimentary environment for the Sietiņi Fm. (lower part of the Gauja RS).

Deposits of the upper part of the Gauja RS (Lode Fm.) in NE Latvia and SE Estonia are dominated by clayey deposits with large lenses of yellowish-grey, very fine-grained clays (Kuršs 1992). As suggested by Kuršs (1975, 1992) and Blāķe (2010), these clays were accumulated in the depressions of large slumps. The grain-size of deposits (dominant clayey fractions) and the widely developed slump depressions, filled with very fine-grained clay, indicate the development of a submarine slope of the delta (Kuršs 1992). Pontén & Plink-Björklund (2007) advocated that there was a change from the progradation to aggradation from the lower to the upper part of the Gauja RS, coupled with a decrease in tidal influence and a decrease in the coarse-grained sediment input. Later they interpreted the clayey deposits of the Gauja RS (clays of the Lode Fm.) as the overbank deposits and delta plain lakes (Pontén & Plink-Björklund 2009). That study, however, does not explain the origin of the clay-filled depressions, typical for the Lode Fm. Thus the previous researchers agreed on a general fining-upwards trend within the Gauja RS, however, different opinions exist on the sedimentary environments for the upper part of the Gauja RS (Lode Fm.).

Kuršs (1992) suggested that the deposits of the Amata RS were formed in a transgressive basin. This basin was wider than the previous, Gauja basin, and the deposits of the Amata Fm. in the northeastern regions of the MDF disconformably cover the older beds, even the Ordovician deposits. Kuršs (1992) also noticed the diverse current orientations in Amata time. He attributed this phenomenon to the decrease in the clastic material supply from the northerly situated provenances combined with the development of a complicated current system, including alongshore currents, in the sea. Pontén & Plink-Björklund (2009) suggested that the deposits of the Amata RS were formed in tide-dominated estuaries. Due to the transgression, sedimentary environments changed from fluvial channels to outer-estuarine tidal bars (Pontén & Plink-Björklund 2009). The transgressive development of the basin during Amata time is suggested in both the above studies.

The results of this study show similarities with the data of previous studies in the area of the Baltic States. The deposits of the Oredezh Beds corresponding to the Gauja RS are rather similar to those of the Sietiņi Fm. from Latvia and Estonia, and their sedimentary environment, all across the northwestern part of the MDF, is suggested to be a fluvially dominated prograding delta plain. The upper part of the Gauja RS, represented by the clayey deposits of the Lode Fm. in Latvia and Estonia, has been observed neither in the study site nor in the neighbouring areas, except for the Pechory quarry in the western part of the Pskov Region. Probably this part of the section was eroded during the end of Gauja time or its composition is sandier in the study area than in NE Latvia, SE Estonia and in the vicinity of Pechory. Thus the deposits corresponding to the lower and upper parts of the Gauja RS are similar by lithological features in the vicinity of Borschovo.

The abundance of the tidal features and the variability of the palaeocurrent directions in the Staritsa Beds that were observed in the study area, are similar to the features typical of the Amata RS in the Baltic States (Kuršs 1992; Pontén & Plink-Björklund 2009). Sandy deposits of the Staritsa Beds in several intervals (1.4–1.7 m, 2.0–2.3 m, 3.6–3.8 m, 5.9–6.1 m) of the Borschovo section contain up to 3 cm large quartz pebbles, often together with clay clasts. In places, including fish bone-beds (layer 12 and the upper part of layer 14), quartz pebbles are abundant, even dominant in the deposits. The siliciclastics of the Amata RS in the Baltic States are mostly fine-grained sandstones (Kuršs 1975), whereas quartz pebble-size material has not been documented yet for these deposits in this territory. The presence of coarse-grained material may suggest low sea-level, erosion and the formation of incised valleys (Catuneanu 2006), which, however, is controversial to the transgressive development of the basin during Amata time (Kuršs 1992; Pontén & Plink-Björklund 2009).

The seaward grain-size decrease in the fluvially transported material is generally characteristic of fluvial–tidal transitional zones, and the coarse-grained material layers may represent the influence of river floods (Dalrymple & Choi 2007; Dalrymple et al. 2015). The study area is situated slightly more inland compared to the territory of the Baltic States (Kuršs 1992), thus the presence of coarse-grained material could indicate a stronger influence of fluvial processes than in the central and western parts of the palaeobasin. Moreover, the study area was closer to the palaeoequator than the territory of the Baltic States and under the influence of a more humid climate (Scotese 2014). Generally, the erosion by flowing water is more intense in areas with humid climate; however, in regions with an arid climate infrequent, but violent rainstorms can result in more erosion than in humid areas, where the soil cover is an obstacle for erosional processes (Nichols 1999). In the humid climate conditions rivers can be fed by the clastics, including coarse-grained material, from mass movement processes (Kirchner et al. 2015). As the amount of coarse-grained, pebbly material tends to decrease upwards in the section of the Staritsa Beds, but the abundance of tidal features slightly increase in the same direction, the pebble-rich material could indicate events of fluvial activity in the tidal to fluvial transitional zone. The influence of a climate change on the grain size of sediments cannot be excluded as well.

Correlation

The lower part of the Devonian succession, exposed in the study area, is represented by white cross-stratified sandstones. These deposits lack fossils, thus their geological age can be evaluated only by the location in the succession and the similarity to other, palaeontologically better characterized Devonian sandstones in the basins of the Oredezh and Luga rivers, such as the outcrops close to Bor, Tolmachovo and Zelenoe Ozero localities (Ivanov et al. 2005).

Supposedly, the Oredezh Beds in the study area represent the lower part of the Gauja RS and are equivalent to the Sietiņi Fm., distributed in the north-eastern part of Latvia (Kuršs 1992). Similar deposits, white cross-stratified sandstones, are present in the outcrop close to the Bor Village, in the Zelenoe Ozero quarry, and the outcrop at the Tolmachovo Village. These objects are situated at a maximum distance of 40 km from each other, in the belt of WSW–ENE orientation, resembling distribution areas of the Devonian formations (Ivanov et al. 2012). The most representative sites to characterize the sedimentary structures and fossils in the Devonian white sandstones are the Zelenoe Ozero quarry and Tolmachovo outcrop that offer wide, well accessible exposures.

Fine- to coarse-grained, very light-coloured sandstone is exposed in these sites. In places this sandstone is gravel-rich and often contains clay clasts. In the Zelenoe Ozero quarry numerous erosional surfaces, which in places change into erosional channels, are present in the sandstones. According to a few measurements, these channels are oriented to south–southeast (Ivanov et al. 2012). The sandstone sequence is dominated by trough cross-stratified beds, which represent 3D subaqueous dunes, formed in the traction currents. In places the cross-beds are up to 1.5 m thick, likely representing sand bars. The only fossils found in the Devonian sandstone sequence of the Tolmachovo and Zelenoe Ozero localities are *Prototaxites* problematic remains (Ivanov et al. 2005). A very large 'trunk' of *Prototaxites*, 55 cm in diameter, has been found in the middle of the exposure at Tolmachovo. Sandstone around this 'trunk' is deformed, probably due to the falling of this object into the unconsolidated sand sediments.

Kuršs (1992) suggests that the white sandstones in the Pskov, Leningrad and Novgorod regions are monomineral quartz ones lacking feldspar. Their heavy fraction is represented by an assemblage of weathering-resistant minerals, such as zircon, tourmaline and staurolite (Kuršs 1992).

Light-coloured, varigrained cross-stratified sandstone with features of slump processes, containing remains of *Prototaxites* but no vertebrate fossils, are likely to be age-equivalent to a very similar sandstone of the Sietiņi Fm., which yields *Prototaxites*. It is distributed in northeastern Latvia and corresponds to the lower part of the Gauja RS. The deposits similar to the Lode Fm., which are distributed in northeastern Latvia, Estonia and the western part of the Pskov Region, have not been recorded in the Oredezh River basin. Thus the rather long period of non-deposition, corresponding to the disconformity between the Oredezh Beds and the Staritsa Beds, cannot be excluded.

The age of the Staritsa Beds in the Borschovo locality can be defined based on the distribution of vertebrate taxa. The placoderm *Eastmanosteus* cf. *pustulosus* has previously been reported only from the lower part of the Gauja RS (Esin et al. 2000). *Psammolepis undulata*, *P. venyukovi* and *Plourdosteus livonicus* were reported from the Gauja and Amata RSs. *Psammosteus praecursor* and *Ps. livonicus* occur only in the Amata interval according to recent data (Glinskiy 2013; Glinskiy & Mark-Kurik 2016). *Asterolepis radiata* is characteristic of the Amata RS and Snetnaya Gora Beds of the Pļaviņas RS. The vertebrate assemblage from the other localities of the Staritsa Beds in the Oredezh River basin usually yields zonal antiarchs *Bothriolepis prima* Gross (locality close to Yam-Tesovo; other localities mentioned by Ivanov & Lebedev 2011, need confirmation) and *B. obrutschewi* (Bor, Goryn′, Yam-Tesovo) (Ivanov & Lebedev 2011). Neither *Bothriolepis prima* nor *B. obrutschewi* have been found in the lower half of the Staritsa Beds in the Borschovo site. The boundary of the Staritsa and Podsnetogorskie Beds is not exposed there; however, the deposits from the Borschovo locality likely represent the most complete section of the Staritsa Beds, including its lowermost part.

However, the influence of taphonomic factors on the taxonomic composition cannot be excluded either: fossil-bearing layers 12 and 13 are represented by varigrained sandstone with gravel and pebbles, deposited in the environment of high velocity. Such a depositional environment is not favourable for the burial of relatively thin and small skeletal elements of early bothriolepids, as well as it prevents the deposition of small scales and other elements of dipnoan, porolepiform and osteolepiform fishes.

CONCLUSIONS

The Oredezh and Staritsa beds, cropping out in the Borschovo section, considerably differ in the grain-size of siliciclastic deposits, sedimentary structures and cross-bedding orientation. Sandstones of the Oredezh Beds most probably are fluvial deposits, as evidenced by their fine- to coarse-grained structures, the presence of erosional surfaces and channels, almost unidirectional current flow and channel orientation, as well as the absence of typical tidal sedimentary structures. Sandstones of the overlying Staritsa Beds were accumulated in a tidally influenced or even tidally dominated environment, as indicated by their tidal structures and variable directions of the cross-bedding. The Oredezh Beds in the study area lack fossils, however, the position in the section and sedimentary features allow correlation with the Sietiņi Fm. of Latvia, corresponding to the lower part of the Gauja RS. The age of the Staritsa Beds is defined based on the distribution of vertebrate taxa as corresponding to the Amata RS. Probably, the deposits from the Borschovo locality represent the most complete section of the Staritsa Beds, including its lowermost part. Rather good preservation of fish fossils, buried together with pebble-sized quartz grains, and wide taxonomic diversity are characteristic of the Borschovo locality, which is not common for the vertebrate localities of the MDF corresponding to the Amata RS.

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Gauja ja Amata lademe Borschovo läbilõike (Leningradi oblast, Venemaa) sedimentoloogia ning biostratigraafia

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Borschovo läbilõikes paljanduvad umbes 15 m ulatuses Givet' ja Frasnesi piirikihid, mis on esindatud osalt põimjaskihiliste liivakivide, argilliitide ning savide seeriaga, mille ülemises osas (Staritsa kihid) leidub erinevate selgroogsete ja taimede kivistisi. Kivimite tekstuur ja struktuur on kihiti erinev. Alumise osa (Oredeži kihid) peene- kuni jämedateralised liivakivid on ilmselt jõetekkelised, kuid Staritsa kihid on kuhjunud, kas loodetest mõjutatud alal või tõusu-mõõnaga rannavööndis. Oredeži kivimitest kivistisi ei leitud, kuid struktuuride analüüs võimaldab korrelatsiooni Sietiņi kihistuga, mis kuulub Gauja lademesse. Staritsa kihtide vanuse (Frasnes) ja kuuluvuse Amata lademesse määravad hästi säilinud vertebraatide kivistised. Nende rohkus on haruldane Ida-Euroopa platvormi Devoni peaväljal.