Trace fossils and ichnofabrics across the Volkhov depositional sequence (Ordovician, Arenigian of St. Petersburg Region, Russia)

Ichnofosilie a ichnostavba v průběhu volchovské sedimentární sekvence (ordovik, arenig) v okolí Petrohradu, Rusko

(10 figs, 2 plates)

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Ichnofabric (bioturbation and bioerosion) patterns show a conspicuous symmetry across the Volkhov depositional sequence, which suggests a close relationship between the ichnofabric and the sea-level change. Bioclastic limestones interpreted as calcareous tempestites show evidence of relatively deep bioturbation (ca. 15 cm) of high intensity. Ichnogenera *Thalassinoides*, *Chondrites*, *Paleophycus*, *? Dolopichnus*, *Trypanites*, *Gastrochaenolites* and *Planolites* participate for the most part in the overall substrate disturbance. Intensive deep bioturbation and even bioerosion occurs in the studied area even below the recently re-interpreted Early/Middle Ordovician boundary. This observation suggests that diverse boring strategies and deep bioturbation, as well as other modern features (e.g., complex tiering, re-visiting of filled burrows), first appeared during the Early Ordovician in this region.

Key words: Ordovician, Baltic Shield, Ichnofossils, Ichnofabric, Eustatic changes

Introduction

Classical Lower to Middle Ordovician sections in St. Petersburg region contain rich and diverse trace fossils assemblages. In contrast to the shelly fauna, which has been collected and studied here since the beginning of the 19th century, trace fossils attract much less attention. Very few ichnotaxa have been mentioned and described for more than two centuries of investigation. These include two types of borings: 1) *Trypanites*-like borings, first described from the region by Vishnjakov – Hecker (1937), and 2) the so-called "Amphora-like" borings (Orviku 1940; Männil 1968). The latter structure has been reported from all over the Baltoscandia (Andersson 1896; Lamansky 1905; Vishnjakov – Hecker 1937; Orviku 1940, 1960; Hecker 1960; Jaanusson 1961; Lindström 1963, 1979; Dronov et al. 1996). Recently it was redescribed as *Gastrochaenolites oelandicus* by Ekdale – Bromley (2001).

Except of these two types of borings, no specific description of any trace fossil is available from the region. Some of the ichnogenera such as *Skolithos, Thalassinoides, Bergaueria,* and *Chondrites* have been only briefly mentioned in the literature (Dronov et al. 1996). However, trace fossil assemblages from the Ordovician of St. Petersburg region are much more diverse. They deserve a special attention as they are important from the viewpoint of palaeoclimatic and palaeogeographic investigations (cf. Dronov – Holmer 1999). The study of trace fossils provides also a good opportunity to formulate an independent approach to the sea-level story. There are two versions of a detailed sea-level curve for the Volkhovian interval. One was based on trilobite ecostratigraphy of the Komstad Limestone in Scania and Bornholm (Nielsen 1995), the second scheme is based on sedimentological studies in St. Petersburg region (Dronov 1998, 1999). The curves are almost identical for the lower and upper Volkhovian, but mismatch severely for the middle part of the Volkhovian. Trace fossil analysis could shed new light on this problem.

The Volkhovian and the underlying beds in the vicinity of St. Petersburg provide extremely rich fossil record of early deep bioturbation and early bioerosion (cf. Droser – Bottjer 1989; Droser et al. 1996). From that point of view, description and interpretation of the ichnological features of the Volkhovian and late Latorpian is crucial for understanding the history of colonization of deep tiers of the sediment and of hard substrates.

The present paper brings general information about the ichnofabric across the Volkhovian sequence in the studied area and thereby it is believed to represent a useful starting point for further investigations. Special attention has been paid to illustrations and interpretative drawings of typical ichnofabric features, which can be helpful for future field studies in various areas showing comparable aspects of bioturbation and bioerosion. In our opinion, the ichnological record gives in this context the best picture of intriguing interplay between sedimentation, erosion and hardening of the substrates (Figs 5, 8, 9, 10). No attention is paid to systematic ichnology, which will be a subject of a separate paper. Material depicted was documented *in situ* and partly collected during May 2002 in the Putilovo quarry locality (Fig. 1). A detailed description of the section and its ichnofabric *bed by bed* was performed at this locality, but its publication is planned after a thorough observation of lateral changes of ichnofabric of individual beds all over the St. Petersburg region, which will be a subject of the next field and laboratory work. Localities Lava and Linna were also visited in 2002 but the material ascertained there was not used for the purpose of this paper.

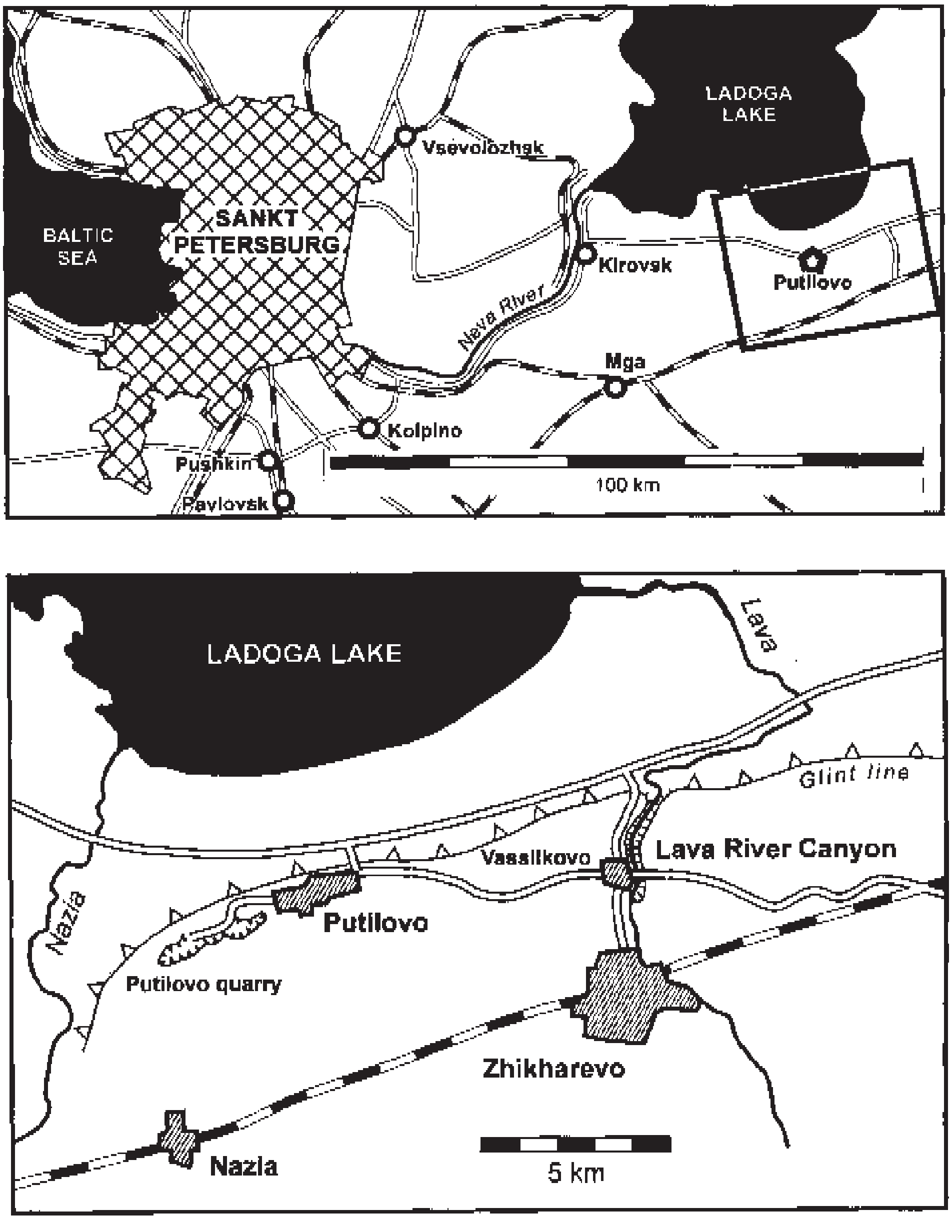

Fig. 1 Sketch map of the St. Petersburg area showing the position of the Putilovo Quarry (marked by an asterisk).

Geological setting

The St. Petersburg region is located at the transition between the southern slope of the Baltic Shield and the northern slope of the Moscow basin. It belongs to the Baltic monocline where relatively undisturbed Vendian and Lower Palaeozoic strata are almost horizontal with a small dip (2.5–3.5 m per km) to the south. Ordovician carbonate rocks occupy an elevated area called the "Ordovician (former Silurian) plateau". The plateau is bounded in the north by a prominent natural escarpment known in the literature as the Baltic-Ladoga Glint (Lamansky 1905). The main natural outcrops of Middle Cambrian-Lower Ordovician rocks in the region follow the line of the Glint. The Cambrian and Tremadocian rocks are represented in the St. Petersburg region mainly by unconsolidated clays and quartz sands. The rest of the Ordovician within the interval from the upper part of the Arenigian to the Caradocian is characterized by carbonate sedimentation.

There is a consensus in the opinion that the Baltic continent migrated from a subpolar to a subequatorial position in the southern hemisphere during the Ordovician (Jaanusson 1973; Lindstrom 1984). Paleolatitude is estimated at about 40–60 °S during the early Ordovician (Torsvik at al. 1992). Latitudinal migration is reflected in the succession of facies from subpolar, predominantly siliciclastic sands and black shales in the Tremadocian through temperate, bioclastic wackestones in the Arenigian–Llanvirnian, to tropical pelmicrites in the Caradocian.

The uppermost Billingenian, Volkhovian and Kundian temperate bioclastic limestones in the St. Petersburg region are interpreted as calcareous tempestites that were deposited in a storm-dominated, shallow-marine environment close to a ramp sedimentary system (Dronov 1998).

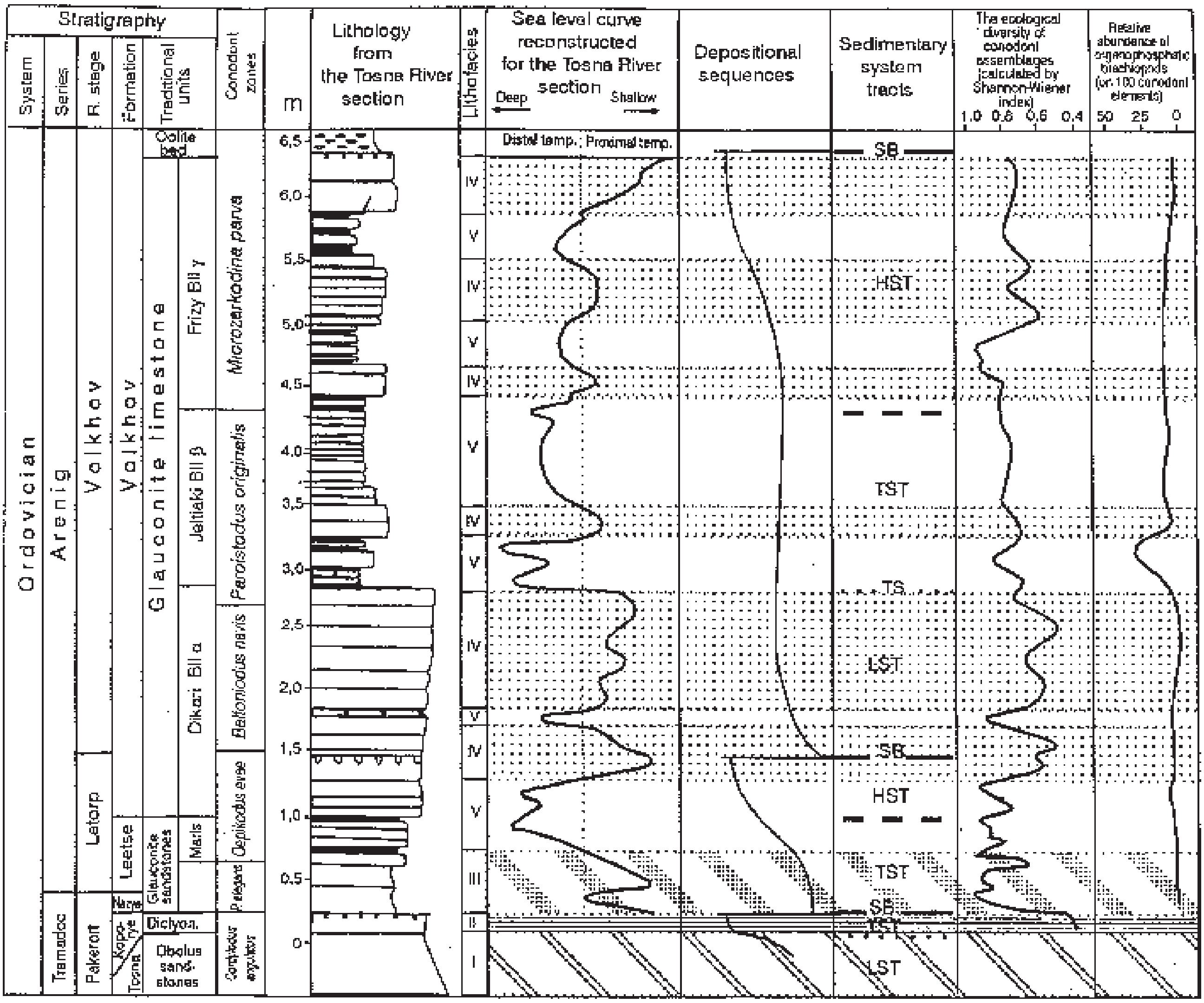

Fig. 2 Lithofacies, sequence stratigraphy, curves of sea-level changes, ecological diversity and abundance in the early Ordovician of the East Baltic. From Tolmacheva et al. (1999).

The storms generated very characteristic sheet-like skeletal sand beds of considerable lateral extent. In the Upper Billingenian and Volkhovian interval, about 30 composite beds and bed packages of storm origin can be traced over a distance of more than 250 km along the eastern part of the Baltic-Ladoga Glint. These beds, which have traditional names given to them by ancient quarrymen, provide a precise time framework for high-resolution regional correlation.

Individual storm beds (3–4.5 cm thick) might have been deposited in a few days, while amalgamated composite beds (up to 20–30 cm) or bed packages (up to 1m) reflect a time interval of 200,000–400,000 years. Carbonate beds have sharp erosional bases with gutter casts and casts of animal burrows. During storm events, the exhumed and partly washed out burrows were filled with sand, forming characteristic casts at the bases of the storm beds. Most of the beds are distinctly graded and consist predominantly of coarse-grained shell debris. Brachiopods, echinoderms, bryozoans, ostracods and trilobites are the main contributors. The limestones vary from bioclastic wackestones to packstones and grainstones. The proximal-distal tempestite trend is obviously recognizable in the sediments.

Stratigraphy

The interval under consideration includes Volkhovian regional stage that roughly corresponds to the "Glauconitic Limestone" in the classification of Lamansky (1905) and directly underlying and overlying beds of the Billingenian and Kundian regional stages, respectively. A new stratigraphic chart of the area based on the section at the Tosna River (approx. 70 km SW of Putilovo) was published by Tolmacheva et al. (1999) and is reproduced herein as Fig. 2. The studied section in the Putilovo quarry is as follows:

Billingenian Regional Stage (BI), (upper Prioniodus elegans and Oepikodus evae conodont zones).

Leetse Formation ("Glauconitic Sandstone").

The Leetse Formation is a formal equivalent of the Glauconitic Sandstone of Lamansky (1905). In the eastern segment of the Glint line, it consists not only of glauconitic sand but also of clays and limestones. Only two uppermost members of the formation will be considered in this paper.

(1) *The Maekula Member* – About 0.55 m of dark green glauconitic sand interbedded with glauconite-bearing clay. The lower 0.20 m of the unit contains a conodont assemblage of the Prioniodus elegans Zone.

(2) *The Vassilkovo Member* – About 1.03 m of greenish-grey and multicoloured sandy and clayey limestone with clay intercalations. The lowermost part is represented by red calcareous clay.

Volkhov Formation ("Glauconitic Limestone").

The lower boundary of the Volkhov Formation coincides with the base of the "Dikari Limestone". This unit represents the lowest part of the "Glauconitic Limestone" in the traditional terminology. In the original sense of Lamansky (1905), BIIa limestone is a formal equivalent of the "Dikari Limestone". Since the lower boundary of the Volkhovian stage has been moved to the so-called "Steklo" nondepositional surface within the Dikari Limestone, the BIIa interval includes only the upper 10 informal units, which correspond to the Saka Member in Estonia (Männil 1966).

(1) *Paite Member* – four limestone beds varying in lithology from clay-like mudstone to bioclastic grainstone with numerous discontinuity surfaces (0.42 m).

Volkhovian Regional Stage (BII), (Baltoniodus triangularis, Baltoniodus navis, Paroistodus originalis and Microzarkodina parva conodont zones).

Volkhov Formation (Glauconitic Limestone).

Volkhovian part of the Volkhov Formation is traditionally subdivided into three units: (1) the Saka Member, which corresponds to the upper part of the "Dikari Limestone" (BIIa) of Lamansky (1905); (2) the "Jeltiaki" Member (BIIb); and (3) the "Frizy" Member (BIIg).

(1) The *Saka Member* (BIIaS) consists of hard, well-bedded, glauconitic limestone, varying from bioclastic packstone or grainstone to marlstone, up to 1.6 m thick. It can be subdivided into 10 elementary informal units traceable for a distance of more then 250 km along the eastern part of the Baltic-Ladoga Glint between the Narva and Syas river valleys (Dronov et al. 1996). The Saka Member contains a conodont assemblage of the Baltoniodus navis Zone. A graptolite assemblage recovered from the basal clay underlying the Staritskji unit in the Putilovo quarry contains *Tetragraptus amii* Elles & Wood, *T. quadribrachiatus* (Hall), *Azygograptus* sp. and *Thamnograptus* sp. (Dronov – Fedorov 1995).

(2) The *Jeltiaki Member* (BIIb) consists of up to 2.2 m thick clayey limestone, yellow, red or variegated in colour, interbedded with clay. Seven informal lithostratigraphic units, varying in thickness from 14 to 39 cm each, can be recognized within the Jeltiaki Member (Dronov – Fedorov 1995). The Jeltiaki Member corresponds to the Paroistodus originalis conodont Zone of the Baltoscandian sequence and the Asaphus (A.) broeggeri local trilobite Zone, probably chronostratigraphically equivalent to the Megistaspis simon Zone of the Scandinavian trilobite sequence.

(3) The *Frizy Member* (BIIg) consists predominantly of nodular glauconitic limestone, light grey or bluish grey in colour, intercalated with numerous lens-like beds of

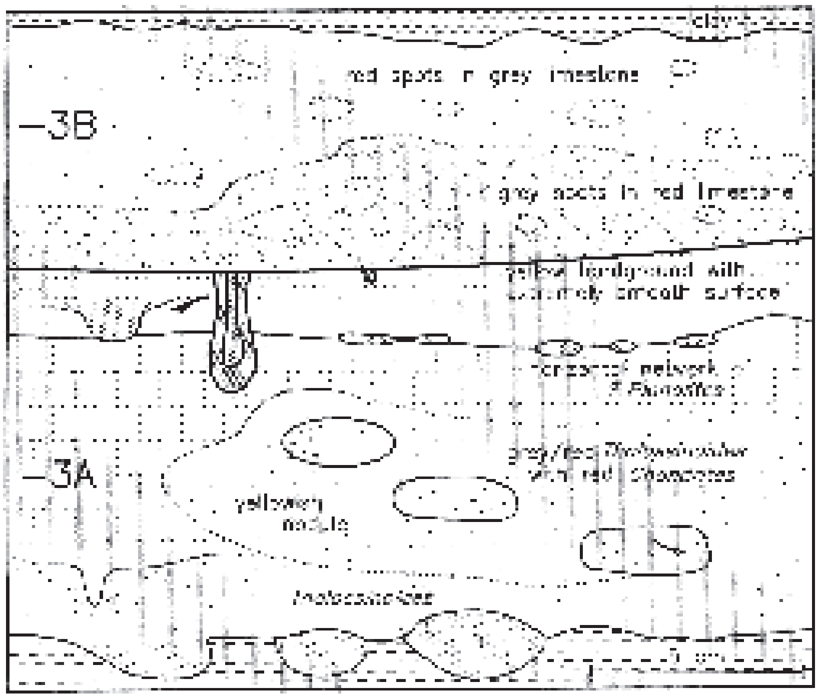

Fig. 3 Schematic drawing of ichnofabric features in the "Margelyia" Beds. Numbering of beds (–3B, –3A) according to A. V. Dronov (MS 2002). Note the prominent hardground with extremely smooth surface and sparse borings at the –3B/–3A boundary.

clay, altogether 2.7 m thick in the eastern part of Baltic-Ladoga Glint. The lower boundary of the unit is accentuated by a bed of bluish-grey clay about 4 cm thick. In sections east of St Petersburg, the Frizy Member can be subdivided into seven informal lithostratigraphic units (Dronov – Fedorov 1995). The Frizy Member contains conodonts of the Microzarkodina parva Zone and trilobites of the Asaphus (A.) lepidurus Zone, which approximately corresponds to the Megistaspis limbata Zone of Scandinavia.

Kundian Regional Stage (BIII), (Eoplacognathus? variabilis conodont zone).

Sillaoru Formation (“Lower Oolite Bed”) consists of calcareous clay and limestone with high clay proportion and numerous iron ore ooids. It can be subdivided into the Nikolskoe (BIIIa NK) and Lopukhinka (BIIIb LP) Members.

(1) *Nikolskoe Member (BIIIa NK)* – 0.65 m of greenish grey clayey bioclastic limestone with numerous small brown iron ooids and ferruginous bioclasts. Trilobite *Asaphus (Asaphus) expansus* (Wahlenberg) marks the base of the Member. The base and the top of the Nikolskoe Member are marked by hardground surfaces with *Trypanites*-like borings. The basal unconformity is interpreted as a sequence boundary.

(2) *Lopukhinka Member (BIIIb LP)* – 0.18 m of clay, calcareous clay and bioclastic limestone intercalations. Both limestones and clays contain numerous large (about 2 mm across), well-developed iron ore ooids. Beds of clay 0.02–0.05 m thick are present at the base, at the top and in the middle of this unit. Trilobites *Asaphus (A.) “raniceps”* Dalman are relatively common. The whole Sillaoru sequence demonstrates a shallowing upward succession.

The Volkhovian Regional Stage represents a full cycle of deposition and is interpreted as a single depositional sequence. It reflects a third-order cycle of relative sea-level changes in the sense of Vail et al. (1977). The hardground surface at the base of the Volkhovian Stage (“Steklo” surface in Russia, “Pustakkiht” in Estonia and “Blommiga Bladet” in Sweden) is very characteristic. It marks a significant gap in sedimentation and is interpreted as a lower sequence boundary (Dronov – Holmer 1999). The ten upper beds of the “Dikari Limestone” (corresponding to the Saka Member in Estonia) represent a lowstand systems tract. At the top of the “Dikari Limestone”, a prominent hardground surface is usually pitted by *Trypanites*-like borings, and it is regarded as a transgressive surface, marking a rapid change from relatively shallow-water to relatively deep-water facies. The “Jeltiaki” and “Frizy” limestones represent the transgressive and highstand systems

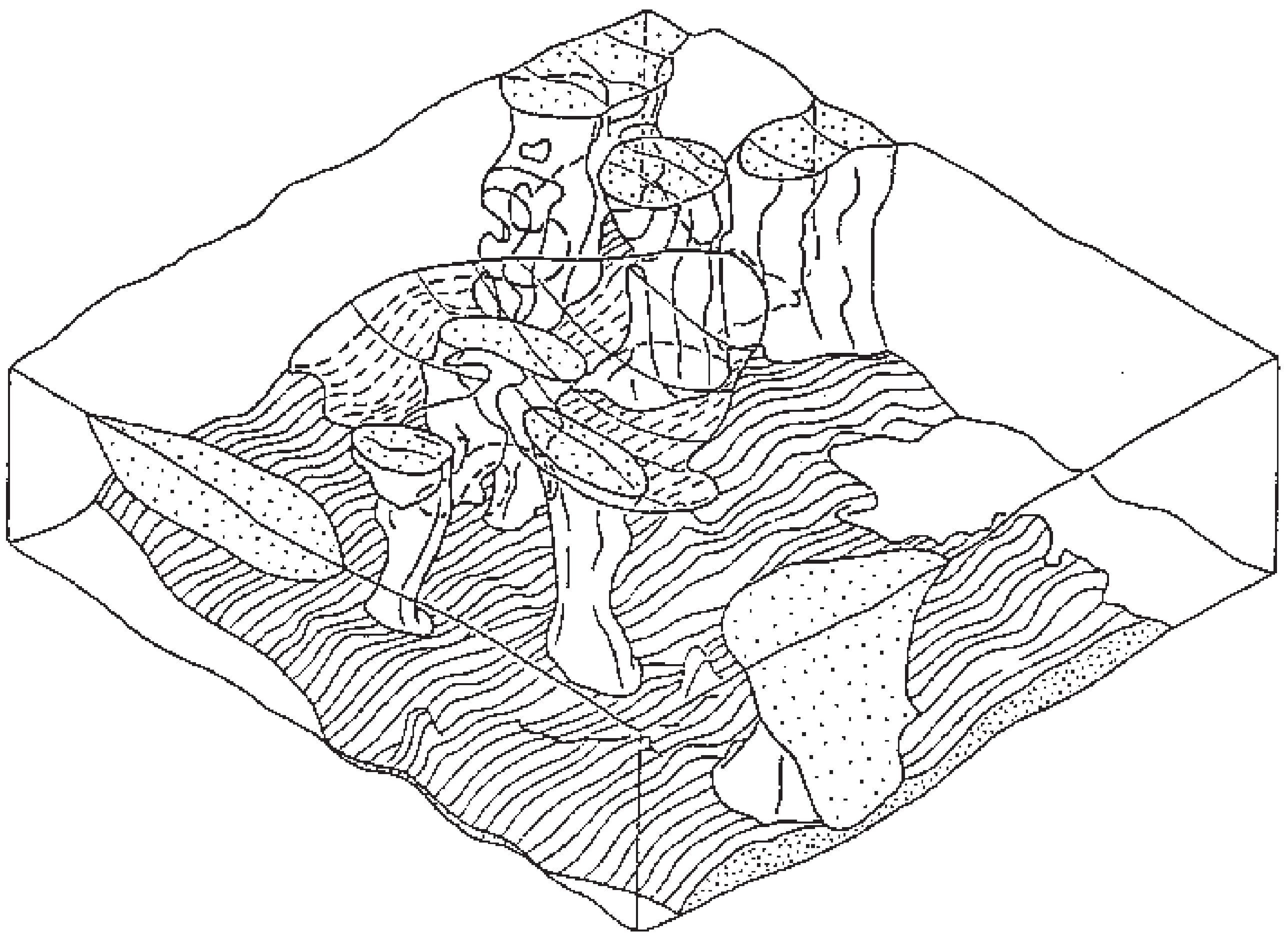

Fig. 4 Block-diagram showing ichnofabric features of the lower boundary of the Volkhov sequence. Size of the sample 11.5 x 11.5 cm. Upper surface of the sample corresponds to the “Steklo” hardground. Drawing by P. V. Fedorov.

tracts, respectively (Dronov 1998). The shallowing-upward succession of the Päite Member (lowermost four beds of the "Dikari Limestone") is interpreted as a highstand systems tract of the underlying Latorp sequence. The Sillaoru Formation ("Lower Oolite Bed") represents a lowstand systems tract of the overlying Kunda sequence (Dronov – Holmer 1999). Erosional surface at the base of the Sillaoru Formation is a sequence boundary.

Trace fossil distribution

The distribution of trace fossils observed in the stratigraphic interval in the Putilovo quarry demonstrates some degree of symmetry. Trace fossils and ichnofabric patterns are described in the following text from the base to the top in ascending order following sequence stratigraphic subdivisions.

1. Trace fossils in the beds underlying the Volkhovian sequence

Top of the Leetse Fm. (Vassilkovo Member, "Mergelyia"), represented by clayey to silty limestones intercalated with claystones shows very rich bioturbation (ichnofabric index 4–5) dominated by *Thalassinoides, Planolites, Palaeophycus*, and *Chondrites* (Pl. I, fig. 1; Fig. 3). All the traces keep specific positions towards the bases/tops of individual beds, showing thereby a stable and rather complex tiering pattern. A hardground developed on the top of bed –3 A shows an extremely smooth surface; however, four specimens of *Gastrochaenolites* aff. *oelandicus* and five small *Trypanites* isp. were found on 1 square metre of the exposed surface (cf. Fig. 3). Uppermost 0.5 m of the Latorp sequence (i.e., Barchat, Melkocvet, Krasnenkiy, Beloglaz and Zeleny beds) shows a striking change in the appearance of hardgrounds, which have numerous big, vertical, usually highly corroded traces best comparable to the ichnogenus *Dolopichnus*, and small irregular borings (Pl. I, fig. 2, 3). Previous (bioturbate) phase of the substrate development showed basically similar features as the top of the Leetse Fm. (*Thalassinoides, Chondrites, Planolites*).

2. Lower boundary of the Volkhov sequence

The lower boundary of the Volkhov sequence is marked by the Zeleny (Green) unit, the thickness of which varies between 0.09 m and 0.30 m in the Putilovo region. This unit is a bioclastic limestone bed enriched in glauconite grains (Pl. I, fig. 7). It is correlated with the Billengenian/Volkhovian boundary interval and includes several smooth hardground surfaces covered by light green glauconitic veneers. One of these surfaces has been named "Steklo" (Glass) by local quarrymen. Lamansky

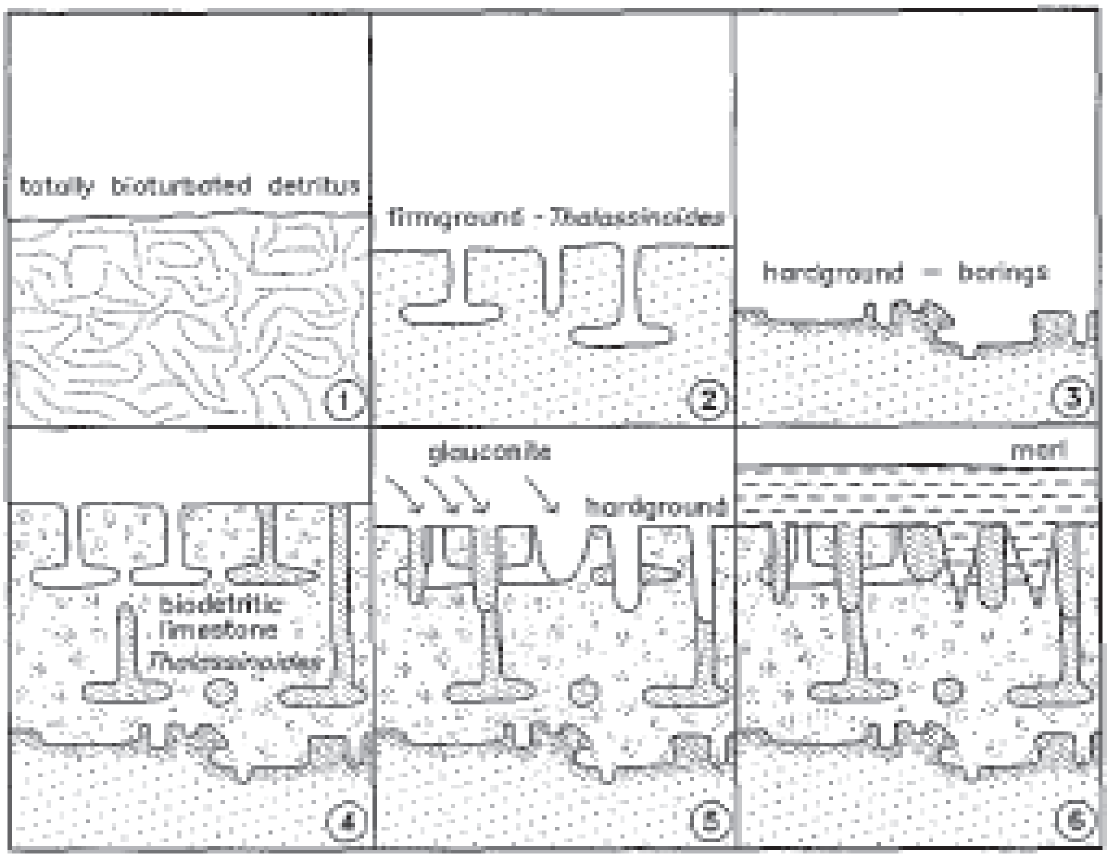

Fig. 5 Lowstand systems tract (Dikari). Ichnologic, sedimentation/erosion and hardening story of the "Krasny" Bed reconstructed according to the exposure on the NW part of the Putilovo quarry. Overall thickness of the depicted sediment is approximately 30 cm.

(1905) traced this surface along the Baltic-Ladoga Glint from the Syas River in the east to the cape of Pakri in the west. It represents a first-order stratigraphic marker, which can be also interpreted as a type-2 sequence boundary (Dronov et al. 1995). The hardground demonstrates a complex boring history with *Gastrochaenolites aff. oelandicus* as the prevailing component (Fig. 4).

3. Lowstand systems tract (Dikari)

The lowstand systems tract of the Volkhov sequence consists of ten distinctive units (from the base of the top): (1) Staritsky; (2) Krasny; (3) Butina; (4) Jelty; (5) Nadjelty; (6) Magonky; (7) Konoplasty; (8) Pereplet; (9) Bratvennik; (10) Butok. The most remarkable of these is the Butina unit, comprising 0.01–0.05 m of relatively soft red marlstone (Pl. I, fig. 4). This unit is the best marker and may be interpreted as a short-term invasion of relatively deep-water conditions. The rocks of the Saka Member are represented by predominantly grey bioclastic packstones or grainstones with numerous scattered glauconite grains. Distinctive hardground surfaces accentuated by yellow goethitic impregnation are very abundant at some levels (Krasny, Jelty, Nadjelty, Konoplasty). Some of these surfaces are pitted by different kinds of borings or preserve partly eroded and secondarily hardened bioturbate traces (Pl. I, figs 5–6, 8). The informal units mentioned above usually consist of 4 to 8 elementary beds 3–4.5 cm thick. Most of the beds are distinctly graded. Brachiopods, echinoderms, bryozoans, ostracodes and trilobites are the main fossils. The uppermost unit of the Saka Member (Butok) has a distinctive hardground surface on the top, marked by an extensive yellow impregnation about 1.5–2 cm deep, and by vertical borings. It is interpreted as a transgressive surface and evidence for an abrupt increase in water depth.

Ichnologically, the lowstand systems tract (Dikari) starts with beds having numerous, strongly bored hardgrounds and remains of *Thalassinoides* ichnofabric and vertical (*Dolopichnus*-like) structures (Fig. 5); at least two horizons bearing *Gastrochaenolites* are also present. The top of the Dikari (Bratvennik and Butok beds) shows very specific trace fossil record including large *Bergaueria*, deep plug-shaped traces (presumably burrows in partly cemented substrate; cf. *Conichnus* and *Bergaueria*; Fig. 6; Pl. II, fig. 1), very large horizontal feeding systems (*Phycodes*; Pl. II, fig. 2) and dwelling networks (*Thalassinoides*).

4. Transgressive systems tract (Jeltiaki)

The transgressive systems tract, represented by the Jeltiaki Member, differs from the underlying rocks of the lowstand systems tract in the presence of a higher proportion of clay material within the carbonate rock, in the presence of numerous clay beds, and in variegated (mostly red and yellow) colours of the rocks. Glauconite is usually rare or absent. The yellow and red colours of the rocks and their finer grain size compared to the underlying and overlying strata point to the relatively deep-water origin of the Jeltiaki Member. It is traditionally subdivided into 7 informal lithostratigraphic units (from the base to the top): (1) Serina; (2) Jeltenky; (3) Krasnota; (4) Tolstenky; (5) Serenky; (6) Lower unit of intercalation; (7) Upper Unit of intercalation (Dronov – Fedorov 1995).

The ichnologic record of the transgressive systems tract starts with a prominent hardground at the top of the Butok. It is marked with small *Trypanites* and probably also small rounded pits (?*Circolites*; Pl. II, fig. 4). The following section of muddy limestones intercalated with claystones has basically two common ichnotaxta, *Thalassinoides* (Pl. II, fig. 6) and *Chondrites*, which often penetrates the fill of *Thalassinoides* (Fig. 8; Pl. II, fig. 8). Maximum ascertained depth of *Thalassinoides* burrows is 14 cm (Fig. 7) but even deeper bioturbation (surprising for the Ordovician) can be estimated. Specific beds are dominated by *Palaeophycus*, *Planolites*, *Macaronichnus* and *Arenicolites*-like (Pl. II, fig. 5) ichnofabrics. Only few examples can be attributed to surface traces preserved in convex hyporelief; they represent the ichnogenera of *Rusophycus* (Pl. II, fig. 7) and *Bergaueria*.

5. Highstand systems tract (Frizy)

The highstand systems tract is represented by the Frizy Member which consists of flysch-like intercalations of

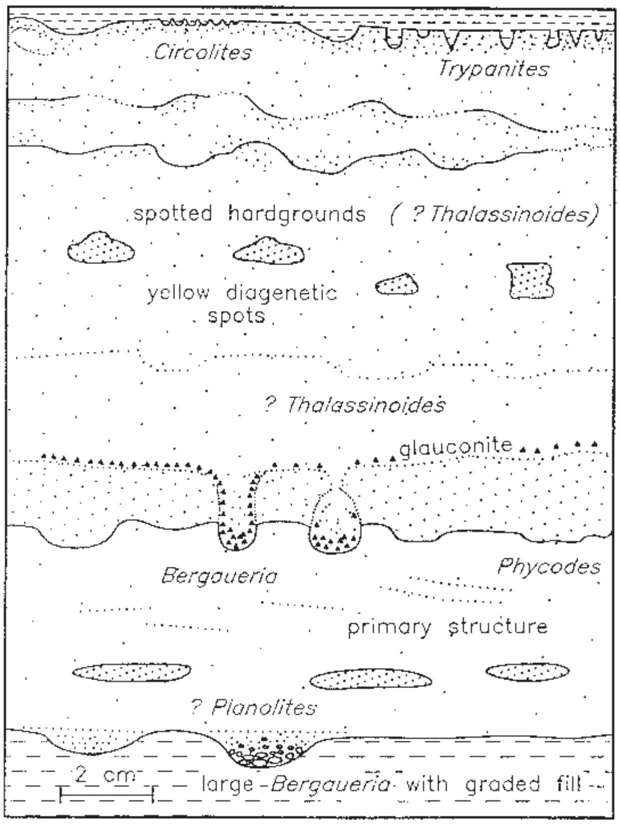

Fig. 6 Lowstand systems tract (Dikari). Schematic drawing of ichnofabric features of the "Butok" Bed (see also Pl. II, fig. 1 for comparison).

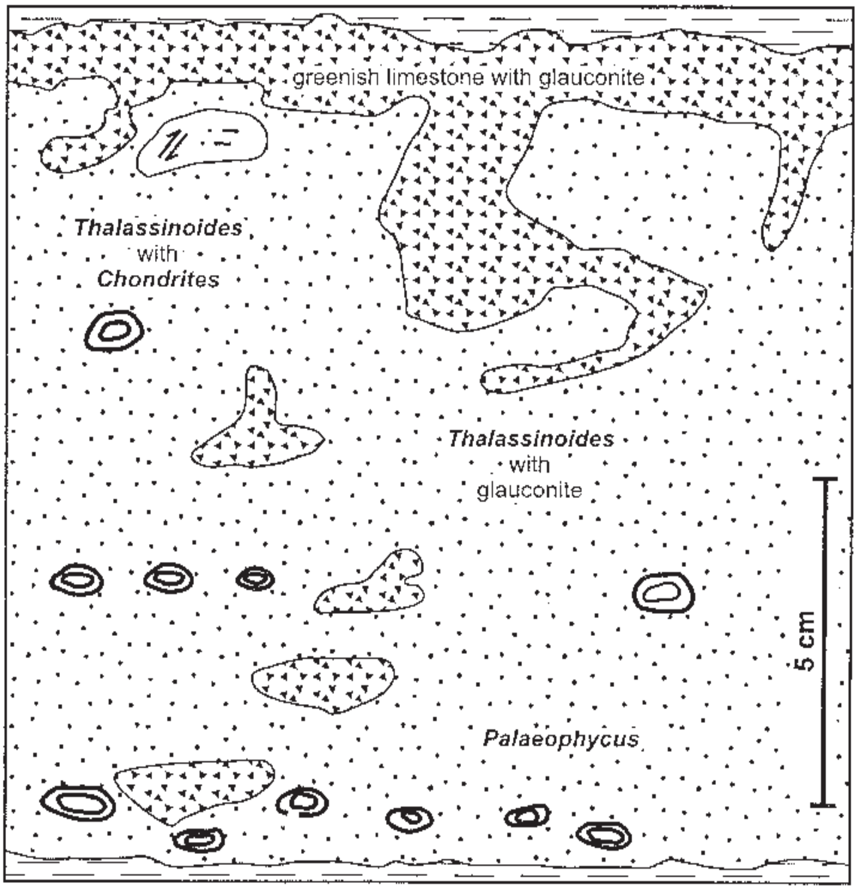

Fig. 7 Transgressive systems tract (Jeltiaki). Schematic drawing of ichnofabric features of the "Tolstenky" Bed. This bed contains deep *Thalassinoides* burrows filled with greenish limestone with glauconite.

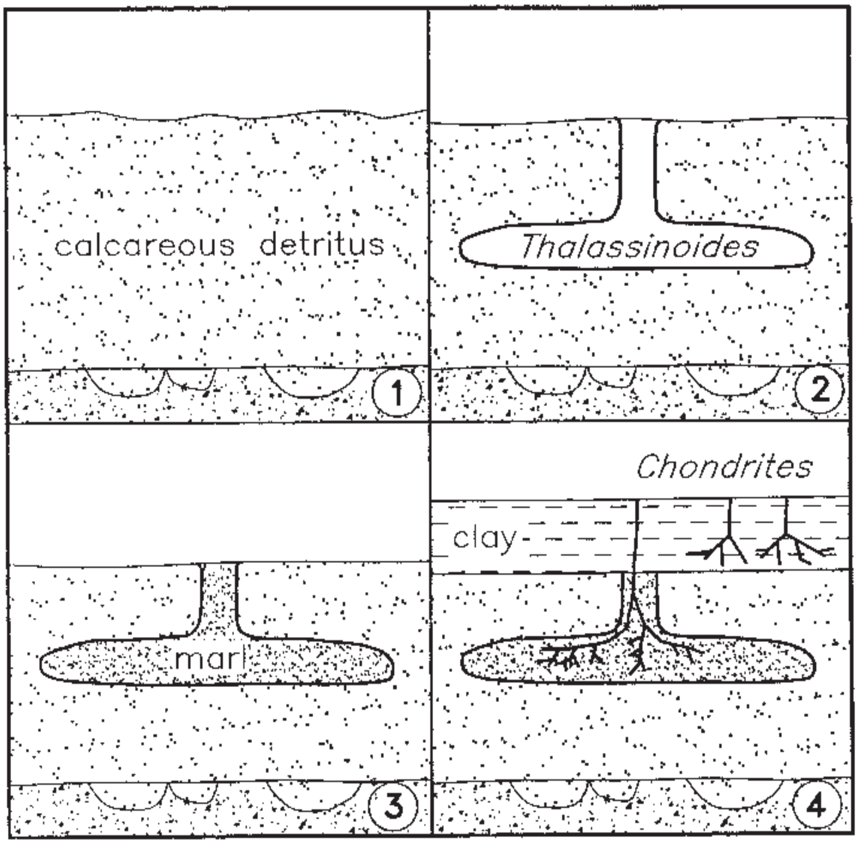

Fig. 8 Transgressive systems tract (Jeltiaki). Ichnologic, sedimentation/erosion and hardening story of the "Jeltenky" Bed reconstructed according to the exposure at the central part of the Putilovo quarry. Overall thickness of the depicted sediment is approximately 7 cm.

greenish grey bioclastic limestone and bluish grey clays. Both limestones and clays contain scattered glauconite grains. The member is traditionally subdivided into 7 informal lithostratigraphical units (from the base to the top): (1) Lower unit of intercalation; (2) Sliven; (3) Middle unit of intercalation; (4) Gorelik; (5) Upper unit of intercalation; (6) Podkoroba; (7) Koroba. The proximal-distal tempestite trend is clearly recognizable in the sediments. The most distal facies of the Frizy Member, however, are closer to the shore than the red-coloured tempestites of the Jeltiaki Member.

The ichnofabric consists chiefly of *Thalassinoides*. Upper portions of the Frizy show, in addition, several beds with *G.* aff. *oelanidicus*, *Bergaueria* and *Trypanites/Circolites* borings (Fig. 9).

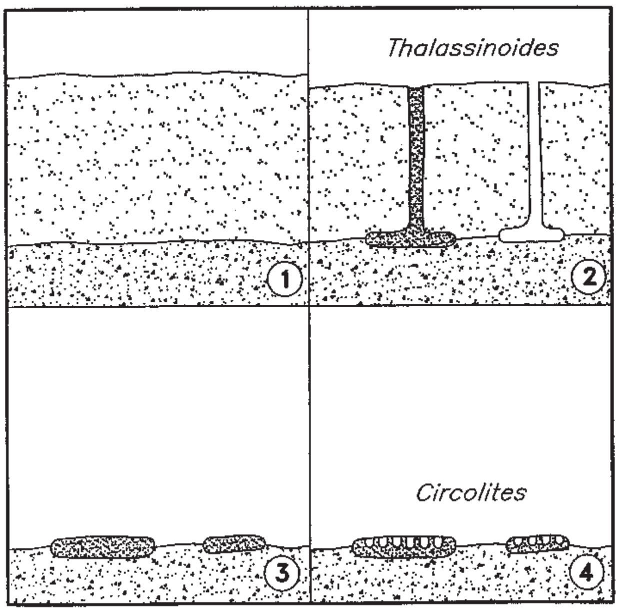

Fig. 9 Highstand systems tract (Frizy). Ichnologic, sedimentation/erosion and hardening story of the uppermost part of the "Upper Unit of Intercalation" Bed reconstructed according to the exposure at the central part of the Putilovo quarry. Overall thickness of the depicted sediment is approximately 8 cm.

6. Hecker-type mud mounds

Organic buildups represent a poorly known but characteristic feature of the Lower Ordovician geology of the St. Petersburg region. One of the largest buildups, about 230 m across and 4–5 m high, is preserved in the central part of the Putilovo quarry on the eastern side of the mining field. The part of the mud mound presently accessible for study is about 50 m across and 4 m high. It rests on the flat hardground surface formed on top of the Paite Member. The central part of the mound consists of a large lens of silty clay and calcareous clay rich in glauconite with two beds of hard, thin laminated sparitic limestones, 0.15–0.19 m thick, near the base. Elementary laminae 3–5 mm thick are accentuated by the distribution of glauconite grains concentrated along the bedding surfaces. The lower part of this lens is represented by greenish grey clay with fine laminae of brownish red clay, nodules and small lenses of grainstone, wackestone and micritic limestone. In the upper part the clay becomes brownish red and reddish grey in colour. Peripherally, within a distance of 25–50 m, the clay is replaced by bioclastic limestone, and all 10 elementary units of the Saka Member become recognizable. The clay hump is covered by a yellow micritic crust up to 0.5 m thick in the upper part of the mound. The outer surface of the crust is accentuated by a hardground surface usually pitted by *Trypanites*-like borings (Pl. II, fig. 3). All the hard surfaces of the mud mounds have association of *Trypanites* and ?*Circolites*, with rare larger borings and secondarily hardened burrows (*Thalassinoides*). Mud beds show frequent *Chondrites* isp.

7. Upper sequence boundary and the overlying beds

Sillaoru Formation (the "Lower Oolite Bed" in traditional terminology) consists of two members. Nikolskoe Member (BIIIa NK) is composed of 0.65 m of greenish grey clayey bioclastic limestone with numerous small brown iron ore ooids and ferruginous bioclasts. It is interesting to note that the iron ore ooids in the unit are usually concentrated in subvertical burrows of *Dolopichnus*-type (Pl. II, fig. 10). Flat pebbles of glauconitic limestone covered by *Trypanites* borings occur in the lower part of the unit. The base and the top of the Nikolskoe Member are marked by hardground surfaces with *Trypanites*-like borings. The basal unconformity is interpreted as a sequence boundary. The Lopukhinka Member (BIIIb LP) is represented by 0.18 m of clay, calcareous clay and bioclastic limestone intercalations. Both limestones and clays contain numerous large (about 2 mm across), well-developed iron ore ooids. Beds of clay 0.02–0.05 m thick are present at the base, at the top and in the middle of this unit.

After a careful determination of individual phases of bioturbation and bioerosion (Fig. 10), it can be shown that the Volkhovian sequence is terminated by a doubled hardground, showing numerous remains of pre-hardening (burrowing) traces (*Thalassinoides* and *Bregaueria*) and borings of *Grastrochaenolites* isp. The overlying beds, i.e. the base of the Kunda sequence, have at least five generations of ?*Dolopichnus* isp. filled with oolitic material. Other traces are represented by *Thalassinoides*, *Chondrites*, and *Palaeophycus*.

Sea-level story

The Ordovician epicontinental basin of Baltoscandia is characterized by an extremely low average rate of sediment accumulation, rarely exceeding 1–3 mm per 1000 years, very flat bottom topography and a long-term tectonic stability. These unique conditions lead to the situation where stratal architecture and facies distribution within depositional sequences depends predominantly on eustasy. The Ordovician succession of Baltoscandia had

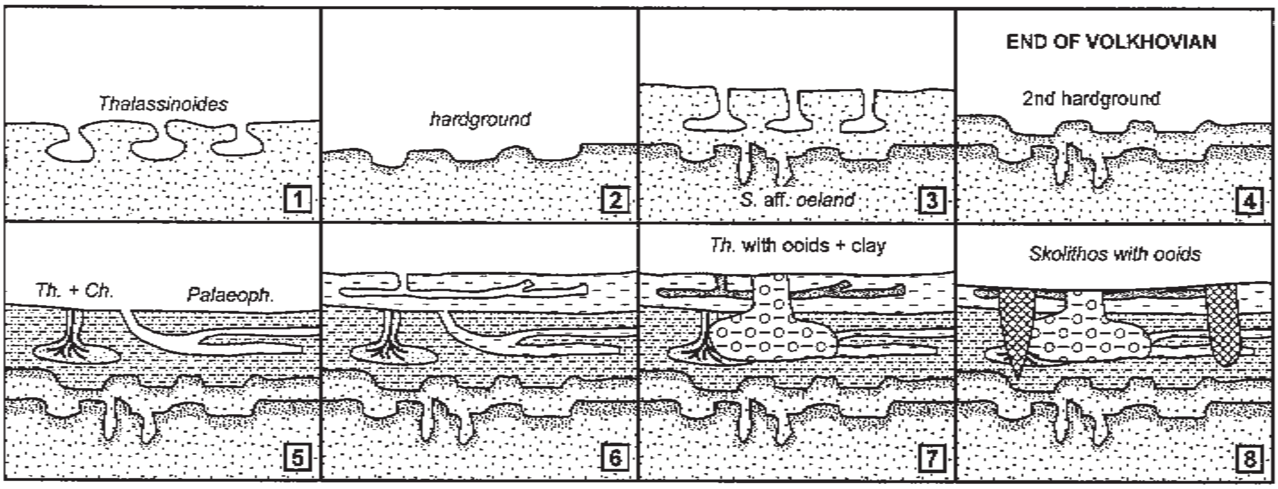

Fig. 10 Upper Volkhovian sequence boundary and the overlying beds. Ichnologic, sedimentation/erosion and hardening story of the uppermost part of the "Koroba" Bed and the basal beds of the Kunda sequence, reconstructed according to the exposure at the central part of the Putilovo quarry. Overall thickness of the depicted sediment is approximately 15 cm.

been subdivided into ten major depositional sequences representing third-order cycles of relative sea-level changes (in the sense of Vail et al. 1977) with an average duration between 4–5 and 9–10 m.y. (Dronov – Holmer 1999).

Sediments of the Volkhov depositional sequence are most widespread in Baltoscandia and demonstrate deepening of the basin. Total area of marine red beds within the Volkhov sequence exceeds the area they cover in the underlying and overlying sequences. Nearshore sediments of this stratigraphical interval were deposited on a carbonate ramp within a shallow-marine, storm-dominated environment. These conditions are favourable for reflection of short-term sea-level fluctuations. Even minor changes in water depth cause an abrupt shift of facies.

About eight different lithofacies have been identified in the Volkhov sequence of St. Petersburg region (Dronov 1999). All of these lithofacies can be arranged according to the relative depth of their deposition on the tempestite ramp profile. Based on the shifts of these facies along the profile, a detailed curve of sea-level changes has been reconstructed (Fig. 2). Major rises of the sea level occurred at the following levels (with reference to traditional bed nomenclature): (1) Krasnenky; (2) Butina; and (3) Krasnota. All of these events are marked by appearance of red coloured deposits characteristic for the central relatively deep-water part of the basin. Important sea-level drops occurred at the following levels: (1) "Steklo" surface (base of the Volkhov); (2) Butok; (3) Tolstenky; (4) Koroba (top of the Volkhov; see Fig. 2). Overall, the sea-level curve is comparable to that constructed by Nielsen (1995) for the Komstad Limestone in Scania. But, in contrary to his conclusion, the data from St. Petersburg Region suggest a greater water depth for the Middle Volkhov (transgressive systems tract) in comparison with the Lower (lowstand systems tract) and the Upper (highstand systems tract) Volkhov. Based on a trace fossils distribution alone we couldn't make such a detailed sea-level curve but the tendency is as follows: (1) major borings (*Gastrochaenolites, Trypanites*) associate with the shallowest deposits and sequence boundaries; (2) well developed *Thalassinoides* and *Bergaueria* systems marks medium water depth in Dikari and Frizy; (3) *Chondrites*, probably the deepest water ichnogenus, is most widespread in Zheltiaki deposits. Thus, trace fossils distribution demonstrates symmetrical patterns and rather supports a deeper water environment for the Middle Volkhovian (Zheltiaki) interval, which fits well with sedimentological observations.

Conclusions

1. Ichnofabric (bioturbation and bioerosion) patterns show a conspicuous symmetry across the Volkhov depositional sequence, which suggest a close relationship between the ichnofabric and the sea-level change.
2. Bioclastic limestones interpreted as calcareous tempestites show evidence of relatively deep bioturbation (ca. 15 cm); both its depth and intensity are high. The ichnogenera *Thalassinoides*, *Chondrites*, *Palaeophycus*, *? Dolopichnus*, *Trypanites*, *Gastrochaenolites* and *Planolites* participate for the most part in the overall substrate disturbance.
3. Despite the acclamation of Sprinkle et al. (1999), intensive deep bioturbation and even bioerosion occurs in the studied area even below the re-interpreted Early/Middle Ordovician boundary. This observation suggests that diverse boring strategies and deep bioturbation, as well as other modern features (e.g., complex tiering, re-visiting of filled burrows), may have first appeared in this region during the Early Ordovician.

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Ichnofosilie a ichnostavba v průběhu volchovské sedimentární sekvence (ordovik, arenig) v okolí Petrohradu, Rusko

Volchovská sekvence přestavuje jedinečný sled poměrně kondenzované sedimentace bioklastických karbonátů temperátní zóny. Ichnostavba těchto usazenin je pozoruhodná z několika důvodů: 1. Mnohonásobné opakování epizod sedimentace a eroze, ze kterého vyplývají složité vztahy protínání jednotlivých generací biogenních textur. 2. Zřetelná symetrie ve výskytu ichnotaxonů a stylů biogenního přepracování v průběhu sekvence poukazuje na významný vliv úrovně mořské hladiny na ichnostavbu. 3. Velká intenzita a hloubka bioturbace, která dosud nebyla pro spodní ordovik předpokládána a nebyla nikde dokumentována. 4. Moderní prvky ichnostavby, jako opakované přepracování již jednou vyplněných stop. 5. Četné případy pro ordovik nové strategie chování – bioeroze. Na celkové bioturbaci a bioerozi mají největší podíl ichnorody *Thalassinoides*, *Chondrites*, *Plaleophycus*, *? Dolopichnus*, *Trypanites*, *Gastrochaenolites* a *Planolites*.

Explanation of plates

All the photos were taken in the field at the Putilovo quarry locality, May 2002. All the collectible samples are housed in the Department of Historical Geology, University of St. Petersburg, Russia. *Photos by R. Mikuláš*

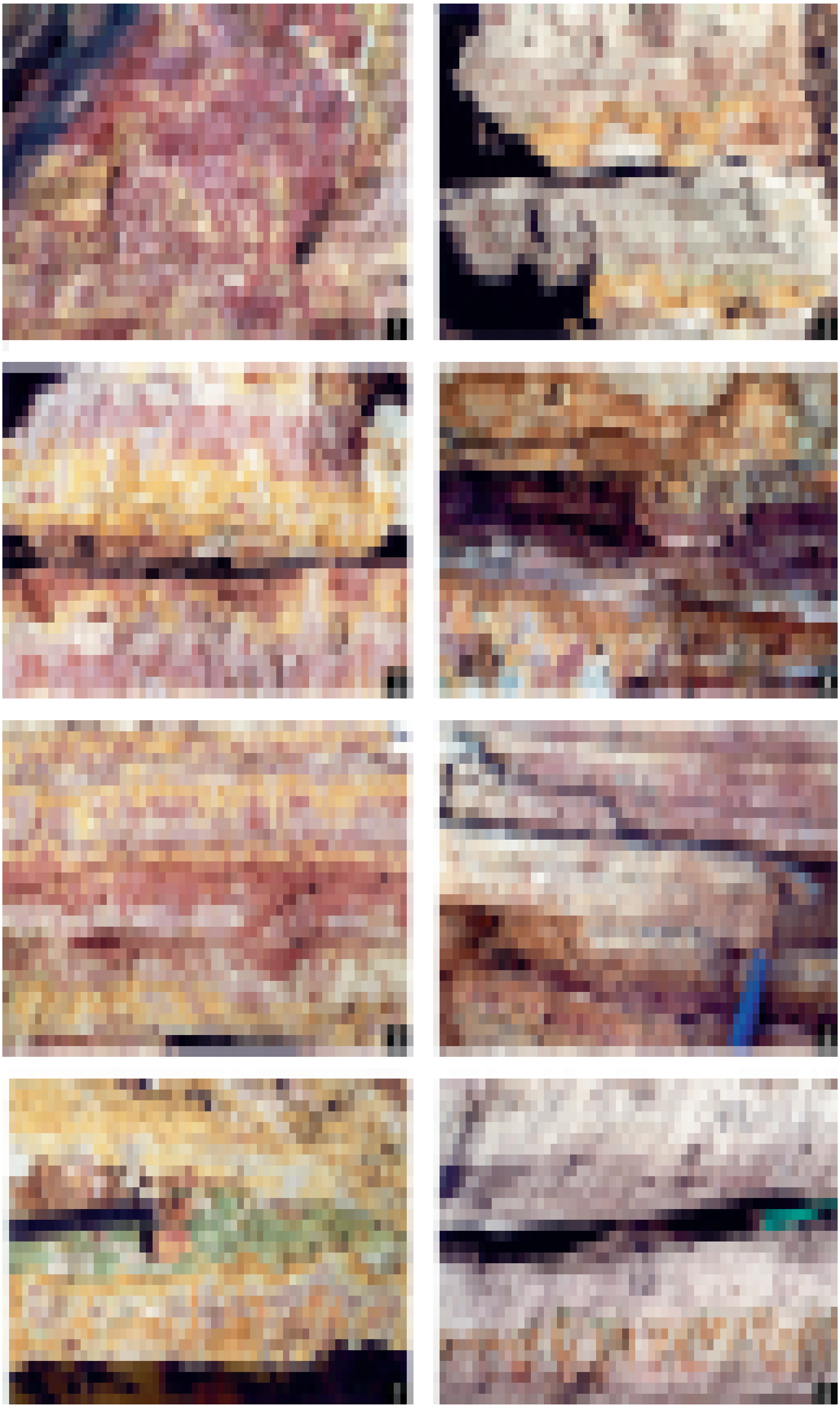
Plate I

1. *Chondrites* isp. (small reddish spots) and *Thalassinoides* Ichnofabric (larger, less conspicuous spots). Top of the Leetse Formation, Bed –1B of Mergelyia.
2. Uppermost part of the Latorp Sequence: Barchat (No. 1) and Melkocvet (No. 2) Beds. Uneven surface of prominent yellow hardground showing strongly corroded borings (?*Dolopichnus* isp.) is overlain by silty limestones with *Thalassinoides* and *Planolites* ichnofabric. Enlarged 0.5 x.
3. Uppermost part of the Latorp Sequence: Krasnenkiy (No. 3) Bed. Several hardgrounds showing essentially vertical borings/burrows (? *Dolopichnus*, ? *Gastrochaenolites*) in various stages of preservation and erosional remnants of horizontal tunnels (*Thalassinoides*). Natural size.
4. Lowstand systems tract (Dikari). The Butina Bed: soft red marlstone showing calcareous nodules, which can be interpreted as parts of compacted systems of *Thalassinoides*. Natural size.
5. Lowstand systems tract (Dikari). The Magonky Bed showing several hardgrounds bearing vertical borings/burrows (? *Dolopichnus*). Enlarged 0.5 x.
6. Lowstand systems tract (Dikari). Beds Staritsky, Krasny, Butina, Jelty, Nadjelty (No. 10, Nj) and Magonky (No. 11). Prevailing feature is a poor-preserved *Thalassinoides* ichnofabric. Length of the hammer 28 cm.
7. Lower boundary of the Volkhov sequence. The "Steklo" surface with numerous burrows and borings. Spike diameter 10 mm.
8. Lowstand systems tract (Dikari). Beds Konoplasty (No. 12 on the photograph) and Pereplet (No. 13). The Konoplasty Bed shows dense vertical structures on hardground surface (? *Dolopichnus* isp.), the Pereplet Bed has poorly visible *Thalassinoides* ichnofabric (darker grey spots). Pencil diameter 7 mm.

Plate II

1. Top of the Dikari Unit: the Butok Bed. Four hardgrounds, one of them bearing a prominent *Conichnus*-like trace. Enlarged 0.5 x.
2. Top of the Dikari Unit: the Butok Bed. Large fan-like horizontal feeding system, *Phycodes* isp.; randomly orientated limbs of *Thalassinoides* isp.; rounded basal parts of *Conichnus*-like trace. Enlarged x 0.15.
3. Hecker-type mud mound. Outer surface of the clay hump bearing dense accumulation of *Trypanites* isp. Enlarged x 0.5.
4. Transgressive systems tract (Jeltiaki). Base of the Jeltiaki Unit: a prominent hardground at the top of the Butok Bed. Relics of Thalassinoides Ichnofabric and patches of small rounded pits (?*Circolites*). Natural size.
5. Transgressive systems tract (Jeltiaki). *Arenicolites* isp. (light grey-filled U-shaped burrow) and *Chondrites* isp. (small reddish spots). Natural size.
6. Transgressive systems tract (Jeltiaki). *Thalassinoides* isp. Enlarged x 0.8.
7. Transgressive systems tract (Jeltiaki). *Rusophycus* isp. Enlarged 1.1 x.
8. Transgressive systems tract (Jeltiaki). *Chondrites* isp. (small reddish spots) penetrating predominantly grey-filled spots of *Thalassinoides* Ichnofabric. Enlarged 0.7 x.
9. Base of the Kunda sequence. Vertical burrows of ? *Dolopichnus* isp. filled with oolitic material. Enlarged x 0.8.

A. V. Dronov, R. Mikuláš, M. Logvinova: Trace fossils and ichnofabrics across the Volkhov depositional sequence (Ordovician, Arenigian of St. Petersburg Region, Russia) (Pl. I)



A. V. Dronov, R. Mikuláš, M. Logvinova: Trace fossils and ichnofabrics across the Volkhov depositional sequence (Ordovician, Arenigian of St. Petersburg Region, Russia) (Pl. II)