GEOLOGICA CARPATHICA, OCTOBER 2006, 57, 5, 415–422

Trace fossils on and above the transgressive surface: substrate consistency and phosphogenesis (Lower Ordovician, St Petersburg region, Russia)

VICTORIA B. ERSHOVA[1], PETER V. FEDOROV[1] and RADEK MIKULÁŠ[2]

[1]Department of Geology, St Petersburg State University, Universitetskaya Emb. 7/9, St Petersburg, Russia;
vika-ershova@yandex.ru; fedorov@gg2686.spb.edu
[2]Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 269, 165 00 Praha 6, Czech Republic;
mikulas@gli.cas.cz

(Manuscript received November 25, 2005; accepted in revised form March 16, 2006)

Abstract: The basal layers of the Leetse Formation (Lower Ordovician, St Petersburg region, Russia) are characterized ichnologically by: 1 — local occurrence of the ichnogenera *Conichnus*, *Bergaueria* and ?*Thalassinoides* at the base. These traces originated by burrowing in consolidated substrate of the underlying black, clayey Dictyonema Shale and were buried by the basal bed of the Leetse Formation; 2 — the layer with camerate burrows (*Amphorichnus* div. isp.), filled with phosphatic substrates, ca 15 cm above the base. Considering the position of the localities of the phosphatized burrows in the basin, we presume that burrows on tops of tectonically uplifted blocks were filled by cryptocrystalline phosphorite matter. Rapid phosphate mineralization points to conditions of shallow burial, high concentration of dissolved pore water phosphate, and suitable redox interval caused by decomposition of organic matter of burrow dweller tissues.

Key words: Lower Ordovician, Russia, St Petersburg region, firmgrounds, platform sediments, trace fossils, phosphate.

Introduction

Trace fossils represent a specific type of geological "memory record" which possesses numerous applications, for example sedimentological, paleobiological and stratigraphic (cf. Frey 1975). The value of a particular assemblage of trace fossils for interpretations is very variable. Whether or not a trace fossil assemblage can give answers to questions of the geological history of the host sediment also depends on completeness and punctuality of the field documentation, and on the possibility of combining ichnological and non-ichnological knowledge.

Lower and Middle Ordovician platform sediments of the St Petersburg region represent a classical area of paleontological, stratigraphical and lithological studies (e.g. Lamansky 1905); more detailed and complete ichnological research, however, has only recently started. Besides the studies directed to the ichnofabric of the lower Middle Ordovician succession (Dronov et al. 2002), unique ichnological structures were also discovered in the Lower Ordovician sediments during the studies focused on sedimentological, stratigraphic and tectonic features of the Baltic-Ladoga Glint, a several hundred of kilometer long linear structure with numerous natural and artificial outcrops (Fedorov & Ershova 2004; Ershova 2005). With the present state of knowledge of the basin, the importance of these trace fossils are the following: 1 — they indicate (better than other kinds of evidence) the degree of hardening of the bottom; 2 — material filling the trace fossils may contain a high percentage of phosphorite, which is in contrast to the composition of surrounding rocks. Therefore, this circumstance opens the question of the origin and distribution of phosphates in the basin.

The aim of the present paper is to describe the trace fossil assemblages and to discuss the two above-mentioned questions of bottom consistency and phosphatization.

Previous work and geological setting

Mainly on the basis of outcrop data, the Ordovician succession of Baltoscandia has been subdivided into ten major depositional sequences (Dronov & Holmer 1999). From the base to the top they are as follows: (1) Pakerort, (2) Latorp, (3) Volkhov, (4) Kunda, (5) Tallinn, (6) Kegel, (7) Wesenberg, (8) Fjaka, (9) Jonstorp, and (10) Tommarp sequence. The studied material comes from the Latorp sequence, which corresponds in the studied area to the Leetse Formation. Its lower part is informally called Glauconitic Sandstone (Schmidt 1881) and consists of rather thin-bedded, chiefly fine- to medium-grained quartz-glauconite sandstones, often with an admixture of clay and carbonate; upwards, they pass into sandy marls with clay intercalations. The overall thickness of the Glauconitic Sandstone varies from 30 to 185 cm in the St Petersburg region.

The underlying Pakerort sequence coincides with the Pakerort Regional Stage. In the St Petersburg region, it comprises shallow-water, cross-bedded quartz sands of the Tosna Formation, overlain by relatively deep water black graptolitic shales of the Kopor'e Formation. The sands and sandstones, which are informally known as the Obolus Sandstone, represent a lowstand system tract, while the black Dictyonema Shale is interpreted as a transgressive system tract (Dronov & Holmer 1999).

Until recently, Lower and Middle Ordovician trace fossils of the St Petersburg region have attracted little attention from researchers. Two types of borings represent a notable exception: 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; Lindstrom 1963, 1979). Recently, a similar structure was described as *Gastrochaenolites oelandicus* by Ekdale & Bromley (2001). Except for these two types of borings, numerous other trace fossils, especially *Skolithos, Thalassinoides, Bergaueria,* and *Chondrites* attracted attention only recently (Dronov et al. 2002; Mikuláš & Dronov 2005). For the Glauconitic Sandstone itself, a preliminary account of its trace fossil content was published by Fedorov & Ershova (2004) and Ershova (2005).

Material and methods

The described material was collected on natural exposures. Because of the horizontal position of the beds in the studied area, the outcrops at the river banks (Tosna and Sablinka rivers at Sablino) usually perfectly expose vertical structures of the rock, and the horizontal aspect is not easily observable. Vice versa, planar exposures on the valley bottoms often show upper bedding planes of sandstone or limestone beds. This is the case at the locality at the Syas River (30 km NW from the town of Volkhov, Fig. 1), where the biogenic structures were found on the lower bedding plane of the well exposed basal bed of the Glauconitic Sandstone. Besides the documentation in situ, about 10 rock samples from Syas and 150 specimens (mostly fills of chambers of trace fossils) from Sablino (Tosna and Sablinka Rivers; Fig. 1) were collected and housed in the collections of the Department of Historical Geology, St Petersburg State University. The laboratory research also included the study of polished and thin sections and X-ray analyses of trace fossil fills and the host rocks.

Synopsis of ichnotaxa

The ichnogenus ***Amphorichnus*** Männil, 1966, was erected for large (several centimeters in diameter), regular, "vase-like" chambers with extremities (i.e. "papillae") at their bases. It remains an incompletely understood ichnotaxon as a modern revision of *Amphorichnus* does not exist yet. We conclude, in analogy to the treatment of similar ichnotaxa, and especially *Gastrochaenolites* Leymerie,

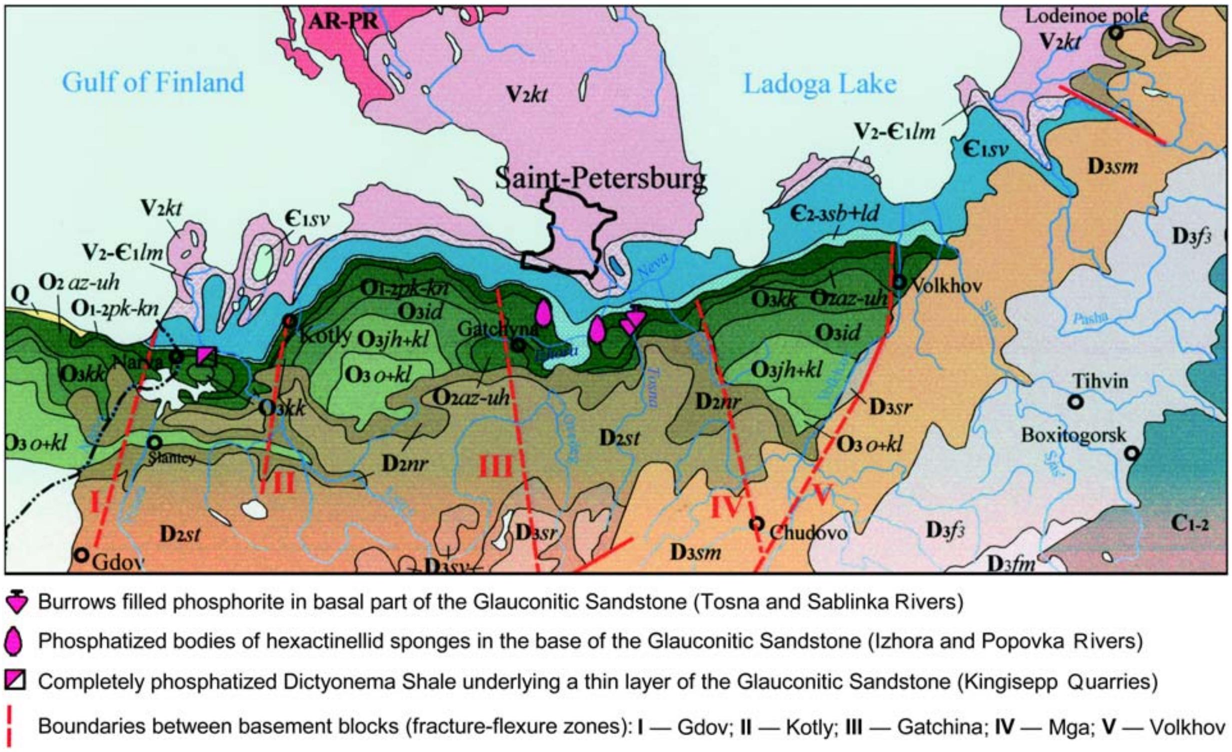

Fig. 1. Location map of localities containing phosphorite-rich sediments near the base of the Glauconitic Sandstone. From Ershova (2005). Abbreviations used: **AR–PR** — Archaean to Proterozoic; **V** — Vendian; $\mathbf{E_1}$ — Lower Cambrian; $\mathbf{E_2}$ — Middle Cambrian; $\mathbf{E_3}$ — Upper Cambrian; $\mathbf{O_1}$ — Lower Ordovician; $\mathbf{O_2}$ — Middle Ordovician; $\mathbf{O_3}$ — Upper Ordovician; $\mathbf{D_2}$ — Middle Devonian; $\mathbf{D_3}$ — Upper Devonian; **C** — Carboniferous; **Q** — Quaternary. For detailed explanation of the geological map see Ershova (2005).

that the diagnosis of *Amphorichnus* should be broadened, and should include all drop-like, bulbous or vase-like burrows in soft substrates. *Amphorichnus papillatus* Männil, 1966 is so far the only ichnospecies attributed to the ichnogenus. Bulbous and "torpedo-like" forms have not been given ichnospecific names yet. Traces attributable to *Amphorichnus* ispp. were found in the basal beds of the Leetse Formation in the valleys of Tosna and Sablinka Rivers (Fedorov & Ershova 2004).

The ichnogenus ***Bergaueria*** Prantl, 1945 is represented by shallow, hemispherical to cylindrical solitary burrows (convex hyporeliefs or full reliefs) circular in section, perpendicular to bedding planes. Their diameter is mostly 10–20 mm; the ratio depth/diameter varies in most cases from 0.5 to 2.0. The base of burrows is hemispherical, rarely flat or conical. Its surface is smooth and a wall lining is absent. Trace fossils of the above-described morphology occur on the basal bedding plane of the Leetse Formation in the Syas River Valley (Ershova 2005).

The ichnogenus ***Conichnus*** Männil, 1966 consists of conical, deep holes (more often preserved as their fills in lower bedding planes). The base of the cone is not sharp but finger-shaped; the depth of the trace is 1.5 to 2× higher than its diameter; its wall unlined, sometimes bearing an irregular radial ornament (modified after Pemberton et al. 1988). Similar to *Bergaueria*, *Conichnus* occurs locally at the base of the basal beds of the Leetse Formation in the Syas River Valley. It probably represents the dwelling burrows of anemones or similar organisms.

Thalassinoides Ehrenberg, 1944 consists of three-dimensional burrow systems consisting predominantly of smooth-walled cylindrical tunnels. They branch more or less systematically; branchings are Y- to T-shaped. Tunnels may be enlarged at bifurcation points. Each system usually has essentially a horizontal component (subsurface tunnel network) and vertical shafts joining the tunnels with the bottom surface. At the described sites, no complete networks of *Thalassinoides* have been found. Segments of tunnels connected to the chamber-like traces at and above the base of the Leetse Formation, however, can be attributed with some reservation to the ichnogenus.

The ichnogenus ***Gastrochaenolites*** Leymerie, 1842 is one of the most frequent boring structures in the fossil record. It consists of drop-like chambers of circular, elliptical, almond-shaped or nut-shaped cross-section; the cross-section of the neck region may differ from that of the lower part of the chamber. Well-known drop-like structures found in hardgrounds of the Volkhov sequence have been placed in *Gastrochaenolites* by Ekdale & Bromley (2001) under the name *G. oelandicus*. However, the situation is complicated both by the presumed variability of substrates, and by the variability of the trace itself, which are not only drop-like, but also spherical, pencil-like or conical. In the Volkhov sequence, it is evident by cross-cutting of large bioclasts that at least some of these structures are real borings into a hard substrate. In the basal layers of the Leetse Formation, no such evidence was found. However, the morphological similarity of *Amphorichnus* isp. (div. isp.) from the Latorp sequence and *Gastrochaenolites* ex gr. *oelandicus* from the Volkhov sequences is notable.

Ichnofabrics

In the basal beds of the Leetse Formation in the Tosna and Sablinka River Valleys, the burrows are up to 10 cm long and 1–4 cm wide and are concentrated on the top of the homogeneous bed of quartz sand, which are 8–18 cm thick and directly overlie black shales (Dictyonema Shales) of the Kopor'e Formation (Fig. 2). The burrows are usually vertical, vase-like, heart-shaped, pumpkin-like or amphora-like. Most of them occur solitarily but locally amalgamation of 2–3 burrows can also be found. The apertures of the trace fossils coincide with the top surface of the basal bed. Fill of the burrows is hard, and the individual specimens can be easily extracted from the host sand/sandstone. Petro-

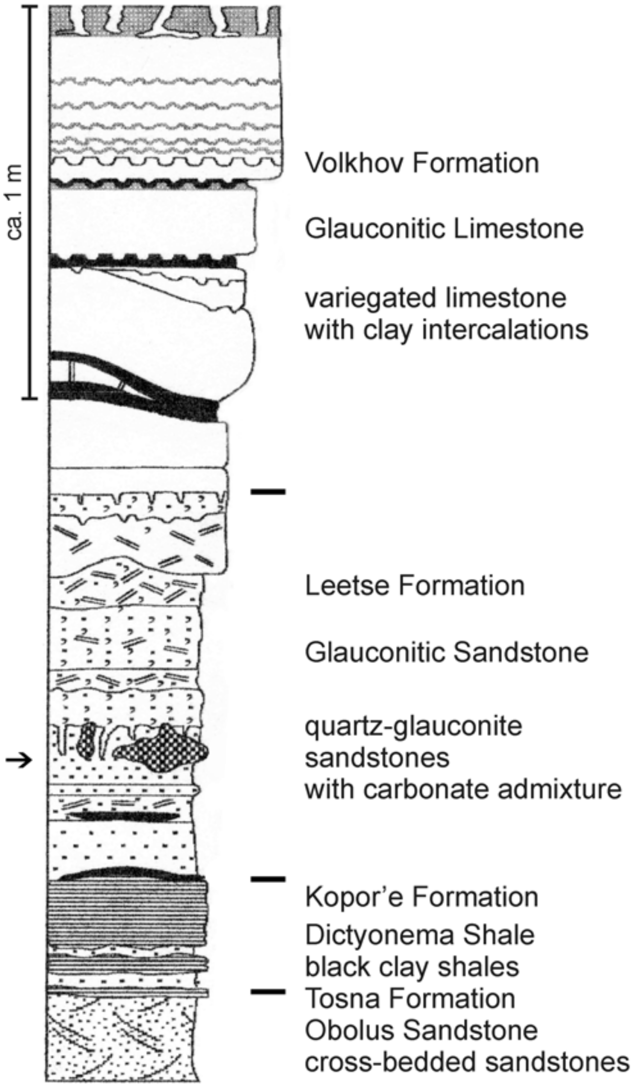

Fig. 2. Schematic drawing of the geological profile at the right bank of the Tosna River, ca. 200 m N of the Sablino Waterfall. The layer rich in phosphatized burrows is marked by arrow.

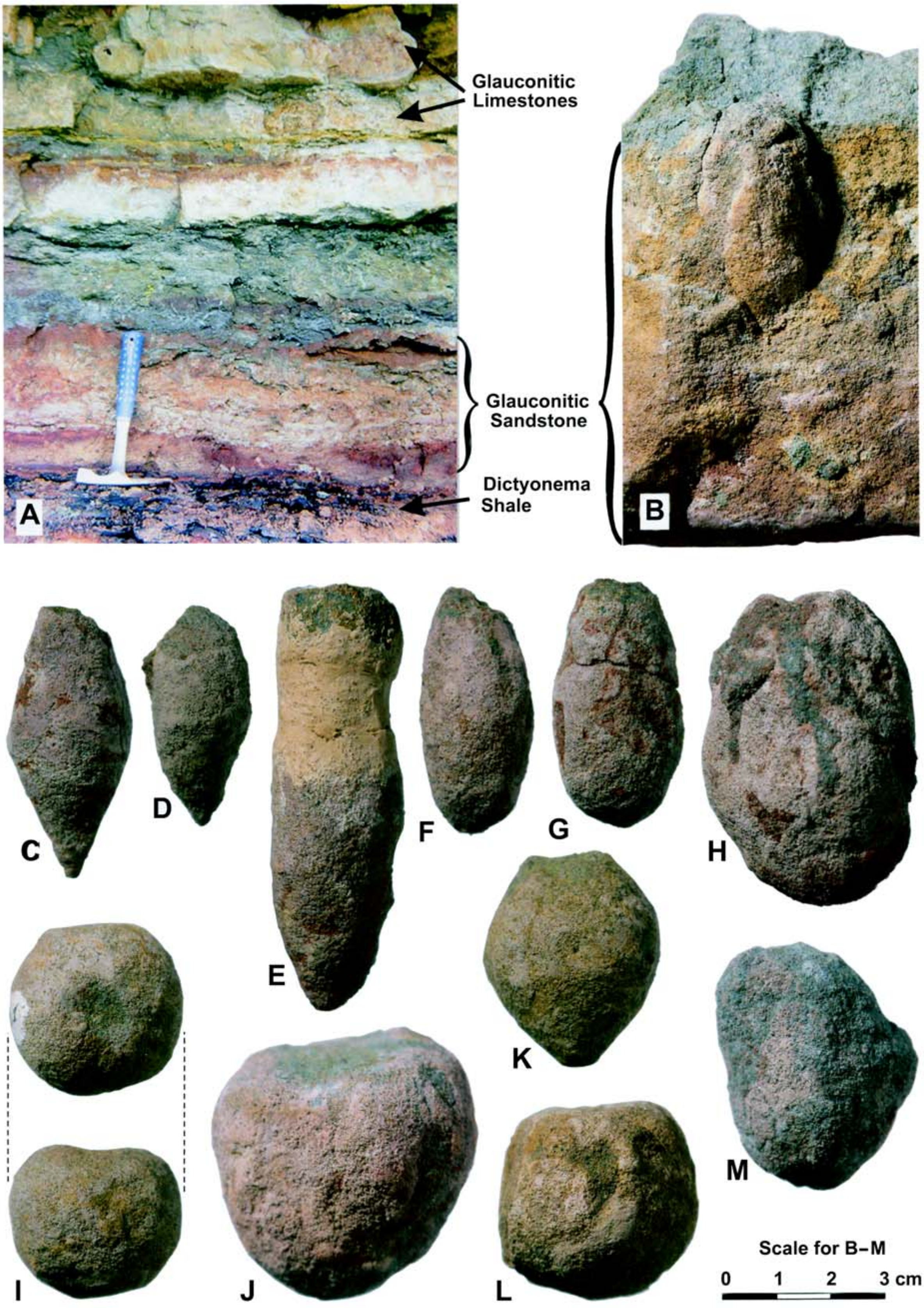

Fig. 3. A — Photograph of the lower part of the profile as shown in Fig. 2, Tosna River at Sablino; **B** — in situ preserved *Amphorichnus* isp. The bracket shows the stratigraphic position of the finding in the profile in Fig. 3A; **C–L** — *Amphorichnus* ispp. Phosphatized burrows showing the variety of shapes. The same locality and layer as Fig. 3B.

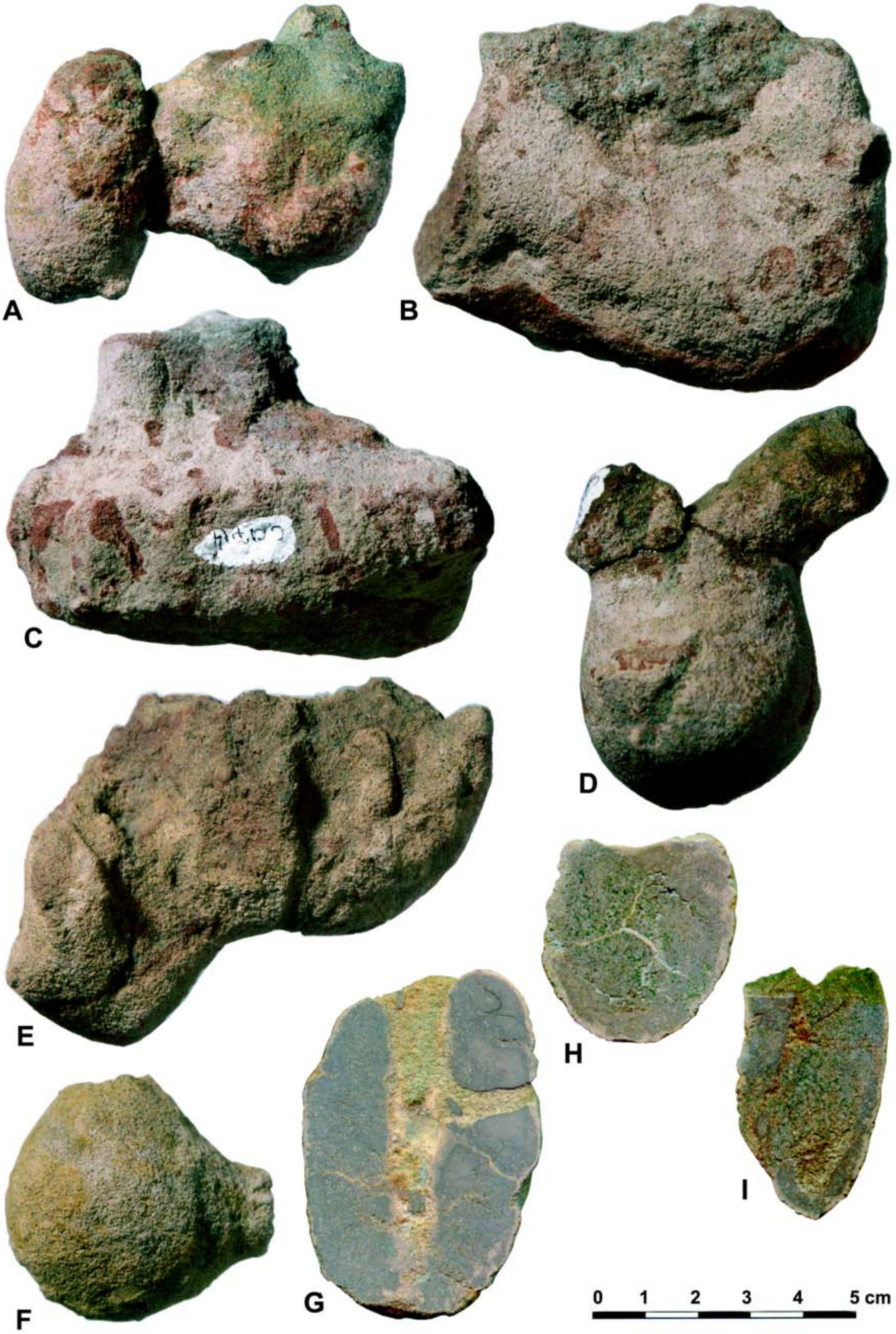

Fig. 4. A–I — *Amphorichnus* ispp. Phosphatized burrows; the same locality and layer as Fig. 3B.

graphically, the fill is represented by cryptocrystalline phosphorite and quartz grains in variable proportion, but phosphorite mostly prevails, having scattered quartz grains. Only occasionally, nearly pure phosphorite, or vice versa, sandstone with phosphorite cement, may form the burrow fill. The central parts of the burrows are often broken by syneresis cracks. Some of the burrows resemble the amphora-shaped ichnospecies *Amphorichnus papillatus* Männil, 1966, as the characteristic "papilla" at the bottom of the trace fossil can be recognized. Other burrows are best understood as potentially new ichnospecies of *Amphorichnus* (see the Synopsis of Ichnotaxa) (Figs. 3,4).

Basal beds of the Leetse Formation in the valley of the Syas River preserve biogenic structures which extend down into the consolidated substrate of the underlying Dictyonema Shale. Here, a dense population consisting of *Conichnus*, *Bergaueria* and *Thalassinoides* producers made an untypical complex pattern on the basal surface of the Glauconitic Sandstone (Fig. 5).

Substrate consistency

The Dictyonema Shale usually shows no discernible biogenic sedimentary structures, in accordance with most of the classical "black shales". Only partial colonization windows, which can usually be interpreted as short episodes of peturbation of anoxia or dysoxia in the bottom waters can be distinguished occasionally; they are marked by the ichnogenus *Chondrites* (cf. Mikuláš 1992 for an example from the Lower Paleozoic). Thin tunnels of *Chondrites* (usually few millimeters in diameter) could have originated and be preserved most probably in a somewhat consolidated substrate, not in "soupgrounds" (this type of substrate consistency is presumed, e.g. for the black Posidonia Shale of the Jurassic of Germany, cf. Martill 1993). The trace fossils, preserved at the bottom of the Glauconitic Sandstone at the Syas River, point to the even more persistent substrate than of a usual softground: both the conical and drop-like structures undoubtedly represent domichnia, namely chambers used for a relatively long time. These were not lined, nonetheless they did not collapse after the death of the tracemaker as there are evidently several generations of burrows on the surface, and they sustained even the erosion of the whole surface joined with truncation of the upper parts.

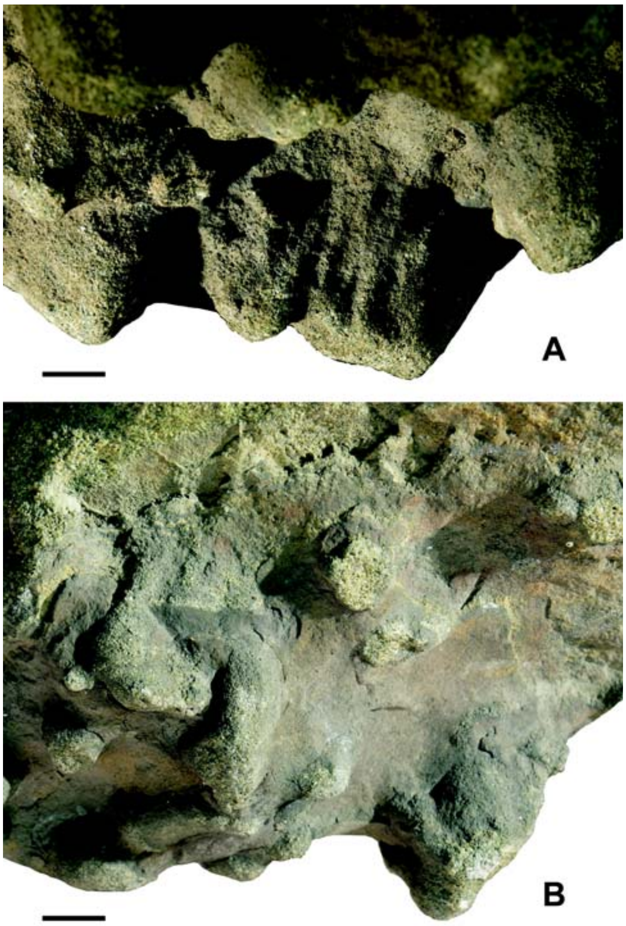

Fig. 5. A — *Conichnus* isp., base of the Dictyonema Shale, Syas River Valley. **B** — *Conichnus* isp. and *Bergaueria* isp., base of the Dictyonema Shale, Syas River Valley. Scale bars = 1 cm.

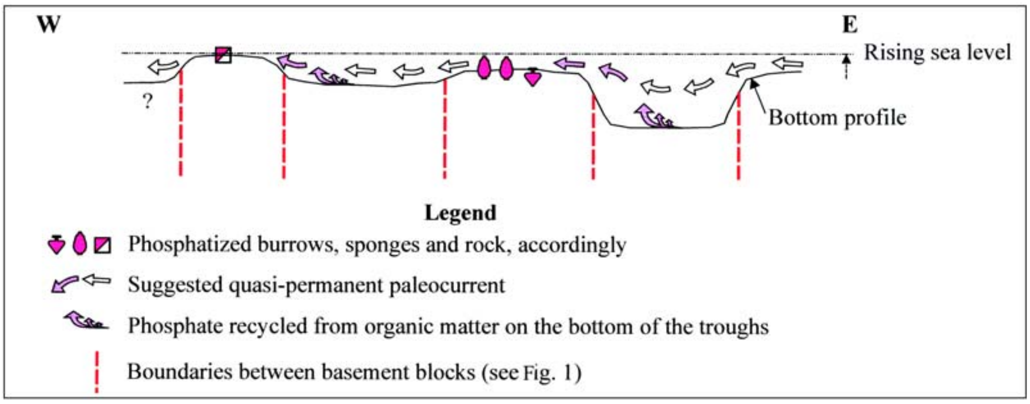

Fig. 6. Proposed localization of transitory deposition of phosphorite on the tops of the uplifted blocks during the late Hunnebergian–early Billingenian transgression. From Ershova (2005).

The presence of a firmground on the top of the unit of the Dictyonema Shale has not been suggested previously. The fact that only one locality provided this fossil record is explained by the limited area of firmground development, which might be influenced by the local tectonic and the resulting sedimentological regime, through which the bottom of a subsiding block was protected from current erosion. Doubtless this substrate was inhabited by different dwellers which loosened the host substrate. Reworked firmground was easily removed by current erosion, and only rare parts might not be eroded. Probably we investigated the first of such a scrap at the Syas River.

The occurrence of firmgrounds in the Glauconitic Sandstone is not surprising in the context of the previous research of the unit (Dronov et al. 2002), but it has not yet been documented so straightforwardly as by the trace fossils in the Sablino area.

Phosphogenesis

The phosphatic filling of the ichofossils in the lower layers of the Glauconitic Sandstone is not relevant to the ichnotaxonomical treatment of these trace fossils. Therefore, it is not pertinent for the assessment of the environment during the colonization of the substrate. This, however, does not restrain the importance of the fill composition to the study of the sedimentation regime of the basin in the period which followed immediately after the death of chamber producers. The formation of phosphorite requires elevated phosphate ion concentrations, which commonly result in marine pore-water from the degradation of organic matter in areas of upwelling (e.g. Compton et al. 2002).

According to our research at the base of the Leetse Formation, phosphate-rich rocks are known in three different forms: 1 — phosphatic fillings of the trace fossils *Amphorichnus* ispp. at the Tosna and Sablinka River Valleys SE of St Petersburg; 2 — phosphatized body fossils of hexactinellid sponges at Izhora River SE of St Petersburg; 3 — "Dictyonema Shales" cemented with phosphorite in the vicinity of Kingisepp town west of St Petersburg (Kingisepp Quarries). The distribution of the phosphatized rocks corresponds well with the position of tectonic blocks recognized in the Baltic paleobasin, namely the basin of the epeiric sea, which covered the St Petersburg area during the Early Paleozoic (Fig. 6). Phosphatization took place on the tops of tectonically uplifted blocks during the transgression of the late Hunnebergian–early Billingenian; the proposed source of phosphate may have been located in relatively deeper water over the subsiding blocks. Phosphate-enriched water was brought on the top of elevated blocks by local semi-permanent upwellings. Phosphorus, probably assimilated by microorganisms, precipitated on the bottom surface. Dispersed organic matter was decomposed. This process elevated phosphate ion concentration in the porewater.

Relatively large dead bodies of burrow-dwellers could provide a suitable substrate for phosphorite (apatite) precipitation from dissolved porewater phosphate, because of a high redox interval. Alternatively, the burrows could be left by the burrowers and infilled by porous, unconsolidated sediment. After that, the phosphogensis started, being limited to the burrow fills (whereas the initial sediment was already cemented and less accessible to phosphogenesis).

Conclusions

1 — Sediments of the Dictyonema Shale forming the bottom of the Ordovician sea of the St Petersburg region before the late Hunnebergian–early Billingenian transgression were locally consolidated in some places to form a substrate which was close to a firmground. It is demonstrated by the suite of trace fossils (*Conichnus*, *Bergaueria*, *Thalassinoides*) found in the Syas River Valley;

2 — Glauconitic Sandstones (Leetse Formation; late Hunnebergian to Billingenian) have had long colonization windows on firm substrates, as proved by trace fossils *Amphorichnus* ispp.;

3 — The burrows on the top of uplifted blocks were filled by phosphatic substrate. The phosphate was probably delivered by semi-permanent currents from the bottom of the troughs in the basin.

Acknowledgments: The research has been supported by the Grant No. 205/04/0151 of the Grant Agency of the Czech Republic and Grant No. UR 09.01.349 of the University of Russia Grant Agency. We thank the official reviewers, Karl Föllmi (Neuchâtel) and Alfred Uchman (Kraków) for constructive and helpful comments.

References

Andersson J.G. 1896: Über cambrische und silurische phosphor-inführende Gesteine aus Schweden. *Bull. Geol. Inst. Univ. Uppsala* 2, 1895, 133–238.

Compton J.S., Mulabisana J. & McMillan I.K. 2002: Origin and age of phosphorite from the Last Glacial maximum to Holocene transgressive succession off the Orange River, South Africa. *Mar. Geol.* 186, 243–261.

Dronov A.V. & Holmer L.E. 1999: Depositional sequences in the Ordovician of Baltoscandia. In: Kraft P. & Fatka O. (Eds.): Quo vadis Ordovician? Short papers of the 8th International Symposium on the Ordovician System. *Acta Universitatis Carolinae–Geologica* 43, 133–136.

Dronov A.V., Mikuláš R. & Logvinova M. 2002: Trace fossils and ichnofabrics across the Volkhov depositional sequence (Ordovician, Arenigian of St Petersburg Region, Russia). *J. Czech Geol. Soc.* 47, 133–146.

Ehrenberg K. 1944: Ergänzende Bemerkungen zu den seinerzeit aus dem Miozän von Burgschleinitz beschreiben Gankernen und Bauten dekapoder Krebse. *Paläont. Z.* 23, 245–359.

Ekdale A. & Bromley R.G. 2001: Bioerosional innovation for living in carbonate hardgrounds in the early Ordovician of Sweden. *Lethaia* 34, 1–12.

Ershova V. 2005: Litostratigraphy of Latorpian horizons along the Russian part of Baltic-Ladoga Glint. *Unpublished MsD Thesis St Petersburg State University*, 1–150 (in Russian).

Fedorov P. & Ershova V. 2004: Phosphatized burrows from the basal layer of the "Glauconite Sandstone" (Billingen Regional

Stage) of the Tosna River. In: Hints O. & Ainsaar L. (Eds.): WOGOGOB-2004 Conference Materials. *Tartu University Press,* Tartu, 1–33.

Frey R.W. 1975: The study of trace fossils. *Springer,* Berlin–Heidelberg–New York, 1-562.

Hecker R.F. 1960: Fossil facies of a flat hard sea bottom. *Eesti NSV Teaduste Akadeemia Geoloogia Instituudi* 5, 199–227.

Jaanusson V. 1961: Discontinuity surfaces in limestones. *Bull. Geol. Inst. Univ. Uppsala* 40, 21–241.

Lamansky V.V. 1905: The oldest Silurian beds of Russia. *Trudy Geol. Komiteta, Novaja Serija 20, St Petersburg* (in Russian).

Leymerie M.A. 1842: Suite de memoire sue le Terrain Cretace du Department de l' Aube. *Mem. Soc. Geol. France* 5, 1–34.

Lindström M. 1963: Sedimentary folds and the development of limestone in an early Ordovician sea. *Sedimentology* 2, 243–292.

Lindström M. 1979: Diagenesis of Lower Ordovician hardgrounds in Sweden. *Geologica et Palaeont.* 13, 9–30.

Männil R. 1966: On vertical burrows in the Ordovician limestones of the Peribaltic. *Akad. Nauk SSSR, Paleontologichesky Inst. 1966,* 200–206.

Martill D.M. 1993: Soupy substrates: a medium for the exceptional preservation of ichthyosaurs of the Posidonia Shale (Lower Jurassic) of Germany. *Kaupia, Darmstädter Beitr. zur Naturegeschichte* 2, 77–97.

Mikuláš R. 1992: Trace fossils from Early Silurian graptolitic shales of the Prague Basin (Czechoslovakia). *Čas. Mineral. Geol.* 37, 219–227.

Mikuláš R. & Dronov A.V. 2005: Trace fossils and ichnofabrics of the Obukhovo and Dubovik Formations (Kunda and Aseri, Middle Ordovician) in the St Petersburg Region. In: Koren T., Evdokimova I. & Tolmacheva T. (Eds.): The Sixth Baltic Stratigraphical Conference. *Abstracts,* St Petersburg, 75–76.

Orviku K.K. 1940: Litologie der Tallinna-serie (Ordovizium, Estland) I. *Acta Comm. Univ. Tartuensis A* 36, 1–216.

Orviku K.K. 1960: On lithostratigraphy of the Toila and Kunda regional stages in Estinia. *Trudy Inst. Geol. Akad.Nauk Estonskoi SSR* 5, 45–85 (in Russian).

Pemberton S.G., Frey R.W. & Bromley R.G. 1988: The ichnotaxonomy of *Conostichus* and other plug-shaped ichnofossils. *Canad. J. Earth Sci.* 17, 1259–1278.

Prantl F. 1945: Two problematic fossils (traces) from the Chrustenice Formation — d ^{delta} 2. *Rozpr. II. Třídy Čs. Akad.* 55, 3–8 (in Czech).

Schmidt F. 1881: Revision der ostbaltischen silurischen Trilobiten nebst geognostischen Übersicht des ostbaltischen Silurgebiets. *Abt. I. Mem. De l'Acad. Imp. des Sciences de St-Petersbourg, VII Serie, T.XXX, 1.,* St.-Petersbourg, 1–237.

Vishnjakov S.G. & Hecker R.F. 1937: Traces of erosion and synsedimentary disturbances in the Lower Silurian "Glaukonite Limestone" of Leningrad District. *Jubilejny sbornik v chest' N.F.Pogrebova,* Leningrad, 30–45.