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First description of rare *Teichichnus* burrows from carbonate rocks of the Lower Paleozoic of Estonia

Olev VINN [1]
Ursula TOOM [2]

Abstract: *Teichichnus* burrows occur in the Sandbian, Katian and Telychian of Estonia associated with carbonate rocks. It is possible that *Teichichnus* is more common in the Sandbian than in the Lower to Middle Ordovician and in the Silurian. Two ichnospecies, *T. rectus* and *T. patens*, have been identified from the Lower Paleozoic of Estonia. This is the first record of *T. patens* in the Ordovician of Baltica. *Teichichnus* in the Sandbian, Katian and Telychian of Estonia is restricted to the shallowest tier levels. The rarity of *Teichichnus* in the carbonate sequences of the Ordovician and Silurian of Estonia reflects little bathymetric variability and an extremely low sedimentation rate in the shallow epicontinental basin.

Key-words:
- trace fossils;
- *Teichichnus*;
- carbonate rocks;
- Upper Ordovician;
- Telychian;
- Baltica

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Résumé : *Première description de rares terriers de* Teichichnus *à partir de roches carbonatées du Paléozoïque inférieur de l'Estonie*.- Les terriers de *Teichichnus* sont présents dans le Sandbien, le Katien et le Telychien d'Estonie, associés à des roches carbonatées. Il est possible que *Teichichnus* soit plus commun dans le Sandbien que dans l'Ordovicien inférieur et moyen ainsi que dans le Silurien. Deux ichno-espèces, *T. rectus* et *T. patens*, ont été identifiées dans le Paléozoïque inférieur d'Estonie. Il s'agit du premier enregistrement de *T. patens* dans l'Ordovicien de Baltica. *Teichichnus* dans le Sandbien, le Katien et le Telychien d'Estonie est limité aux niveaux les moins profonds. Sa rareté dans les séquences carbonatées de l'Ordovicien et du Silurien en Estonie reflète une faible variabilité bathymétrique combinée à une vitesse de sédimentation extrêmement faible dans le bassin épicontinental peu profond.

Mots-clefs :
- trace fossiles ;
- *Teichichnus* ;
- roches carbonatées ;
- Ordovicien supérieur ;
- Télychien ;
- Baltica

1. Introduction

Trace fossils are common and diverse throughout the Phanerozoic. They are valuable environmental indicators and help us understand the behaviour of extinct organisms (SEILACHER, 2007). The trace fossils of the Ordovician and Silurian have been relatively well studied (SEILACHER, 2007). The Ordovician and Silurian of Estonia (Baltica) has an excellent record of sedimentary rocks and associated fossils, including trace fossils (RAUKAS & TEEDUMÄE, 1997). MÄNNIL *et al.* (1984) report that trace fossils are abundant and distributed all over the palaeobasin, but their diversity is lower than in the Cambrian and Devonian of the region. Recent studies show that Ordovician and Silurian trace fossil association are more diverse than previously expected (TOOM *et al.*, 2017). However, trace fossils of the carbonate rocks from the Ordovician and Silurian of Estonia (MÄNNIL, 1966) have historically received less attention than various groups of shelly fossils. In

[1] *Department of Geology, University of Tartu, Ravila 14A, 50411 Tartu (Estonia)*
Olev.Vinn@ut.ee
[2] *Department of Geology, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn (Estonia)*
Ursula.Toom@ttu.ee

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contrast, Lower Paleozoic trace fossils have systematically been described from Scandinavia and northwestern Russia (STANISTREET, 1989; DRONOV *et al.*, 2002; ERSHOVA *et al.*, 2006; KNAUST & DRONOV, 2013; HANKEN *et al.*, 2016). Recently, several traces have been described from the Ordovician and Silurian limestones of western and northern Estonia (VINN & WILSON, 2013; VINN & TOOM, 2015, 2015; VINN *et al.*, 2014, 2015c). Bioerosional trace fossils (ORVIKU, 1960, 1961; DRONOV *et al.*, 2000; WYSE JACKSON & KEY, 2007; VINN *et al.*, 2015b) and various bioclaustrations (VINN *et al.*, 2015a) have the best record among trace fossils in the Ordovician and Silurian of Estonia. Soft bottom trace fossils of the Ordovician and Silurian of Estonia deserve to be studied in more detail in order to use their full potential as paleoenvironmental indicators. The diversity of soft bottom trace fossils are also indirect indicators of biological diversity in the past seas.

Teichichnus is a fodinichnial burrow that has a good record in Phanerozoic rocks (BUCKMAN, 1996). *Teichichnus* burrows are spreite structures which are characterized by a spreite lamina that formed through the displacement of a limb (SCHLIRF & BROMLEY, 2007). The lamina is composed of successively placed floors of the rising burrow limb, which are designated lamellae (SCHLIRF & BROMLEY, 2007). Eighteen ichnospecies have been described due to high variation of burrow morphology (KNAUST, 2018). However, only four ichnospecies are currently regarded as valid: *Teichichnus rectus*, *T. zigzag*, *T. patens* and *T. duplex* (STANTON & DODD, 1984; FREY & BROMLEY, 1985; SCHLIRF, 2000; SCHLIRF & BROMLEY, 2007; MÁNGANO & BUATOIS, 2011; KNAUST, 2018). Combined modes of feeding are involved in formation of *Teichichnus*, including deposit and suspension-feeding, suggesting that *Teichichnus* is a dwelling trace rather than a feeding trace (KNAUST, 2018). *Teichichnus* is considered the best example of the architectural category "Horizontal burrows with simple vertically oriented spreiten" by BUATOIS *et al.* (2017). In addition to the classical interpretation of polychaetes as producers, many features fit with an interpretation of dwelling echiurans and holothurians (KNAUST, 2018, in press). Arthropods, vermiform organisms and especially annelids have been suggested as possible tracemakers of *Teichichnus* (VOSSLER & PEMBERTON, 1989; DAM, 1990). In Baltica, *Teichichnus* occurs in the Cambrian of Sweden (MARTINSSON, 1965; JENSEN, 1997), Middle Ordovician of the St. Petersburg region of Russia (DRONOV & MIKULÁŠ, 2010) and Upper Ordovician of the Oslo-Asker region in Norway (STANISTREET, 1989).

This paper addresses the following question: how common and diverse are *Teichichnus* burrows in the Ordovician and Silurian of Estonia?

2. Material and methods

A large collection of more than 2500 specimens of trace fossils from the Department of Geology, Tallinn University of Technology, and the University of Tartu Natural History Museum geological collections were searched for *Teichichnus* burrows. All *Teichichnus* specimens were photographed with scale bar using a Canon EOS 5Dsr digital camera.

There are hundreds of well-studied Ordovician outcrops in the northern Estonia covering all the international stages. Similarly, all Silurian stages are present, well exposed and studied in middle and western Estonia. Only relatively shallow water rocks are cropping out in the Ordovician and Silurian exposures of Estonia. In carbonate rocks it is common that color contrast is absent, which impacts preservation of biogenic structures (CURRAN, 1994). Delicate traces or parts of them are rarely well preserved (KNAUST *et al.*, 2013) in carbonates. *Teichichnus* usually occurs in lower shoreface to offshore deposits (PEMBERTON *et al.*, 2012) and is typical for low- to moderate-energy conditions (KNAUST, 2017). Given the above, it may be assumed that *Teichichnus* is an undersampled trace fossil in Estonia, especially in drill cores representing deeper environments.

3. Geological background

During the Ordovician, the palaeocontinent Baltica drifted from the temperate climatic zone into the subtropical realm (NESTOR & EINASTO, 1997; TORSVIK *et al.*, 2013). In the Middle Ordovician and lower Upper Ordovician (Sandbian), the area of modern Estonia (Fig. 1) was covered by a shallow, epicontinental sea. It was characterized by little bathymetric variability and an extremely low sedimentation rate (NESTOR & EINASTO, 1997). Along the entire extent of the ramp a series of grey argillaceous and calcareous sediments accumulated with a trend of decreasing clay and increasing bioclasts in the onshore direction (NESTOR & EINASTO, 1997). During the Katian, the climatic change resulted in an increase in carbonate production and sedimentation rate. The Katian was the time of appearance of the first carbonate buildups in the basin.

During the Silurian, Baltica was located in equatorial latitudes and moving northwards (COCKS & TORSVIK, 2005; TORSVIK *et al.*, 2013). A shallow epicontinental basin covered middle and western Estonia (Fig. 1) with a wide range of tropical environments and diverse biotas (NESTOR & EINASTO, 1997). Five main facies belts have been described from the Baltic basin: tidal flat/lagoonal, shoal, open shelf, basin slope and a basin depression (NESTOR & EINASTO, 1977). The first three facies belts formed are confined to a carbonate platform (RAUKAS & TEEDUMÄE, 1997).

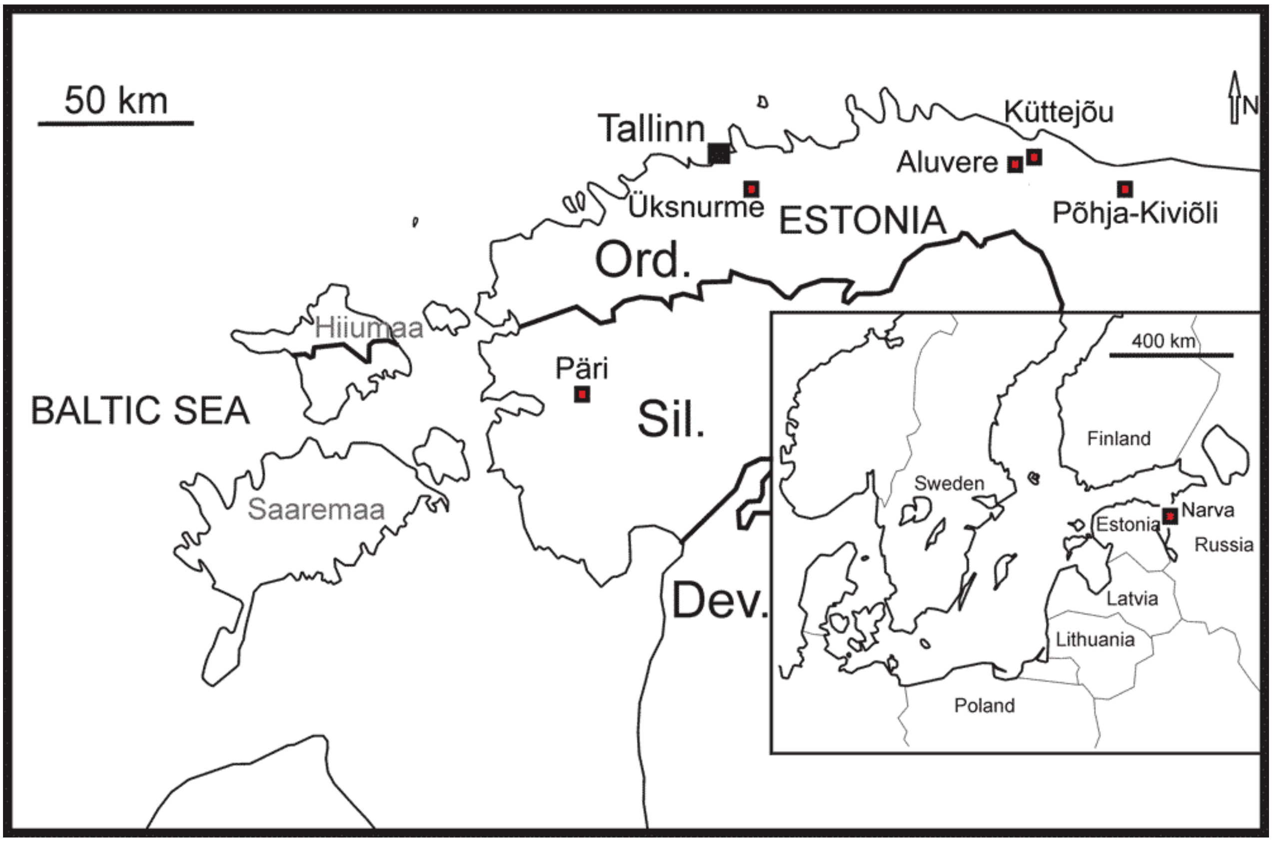

Figure 1: Locality map. Modified after Vinn *et al.* (2017).

4. Systematic ichnology

Ichnogenus *Teichichnus* Seilacher, 1955

Type ichnospecies. *Teichichnus rectus* Seilacher, 1955 - p. 378, Pl. 24, fig. 1; by monotypy.

Teichichnus rectus Seilacher, 1955

(Fig. 2)

Material: Ten burrows preserved in full relief, eight from Sandbian, one from Katian and one from Telychian.

Localities: Narva open pit, Põhja-Kiviõli open pit and Ubja open pit (Sandbian, Kukruse Regional Stage); Aluvere quarry (Sandbian, Haljala Regional Stage); Üksnurme (Katian, Oandu Regional Stage); Päri quarry (Telychian, Adavere Regional Stage) (Fig. 1).

Stratigraphic distribution: lower Sandbian (Kukruse Regional Stage) to lower Telychian (Adavere Regional Stage).

Observations: Horizontal, sometimes slightly inclined, straight to slightly winding, unbranched burrows. The trace fossil consists of convex-down lamellae, forming a wall-like spreite structure. All laminae are arranged retrusively. Terminal burrow tube preserved in some specimens; without strongly upward bending terminal tubes. In lateral view, parallel, more-or-less horizontal lamina form a spreite structure, topped by a tube in some specimens. In transverse section, slight lateral displacements of the lamina can occur. Height of the trace is 1.5 to 6.0 cm. Length of the trace is 7.2 to 14.2 cm. Width of a single trace can be slightly variable. Maximal width of the trace is 0.25 to 3.5 cm. Thickness of individual laminae varies from 0.8 to 12 mm. Silurian burrows are markedly smaller than Upper Ordovician ones.

Note: Knaust (2018) has provided a detailed synonymy of *Teichichnus rectus*.

Teichichnus patens Schlirf, 2000

(Fig. 3)

1992 *Teichichnus* ichnosp. (ichnosp. nov.) Mikuláš, p. 328, Fig. 2; Pl. 7 fig. 2C.
2000 *Teichichnus patens* Schlirf, p. 173, Pl. 6, fig. 5.

Material: Single burrow preserved in full relief.

Locality: Narva open pit (Sandbian, Kukruse Regional Stage) (Fig. 1).

Observations: Horizontal, predominantly straight, branching burrows. Burrows consist of gutter-shaped retrusive laminae. Terminal burrow tube not preserved. Branching via bifurcation at acute angles, branching with up to three branches from a central burrow. Total height of burrow 1.0 cm, burrow width 0.4 to 0.9 cm, total length of burrow 12 cm.

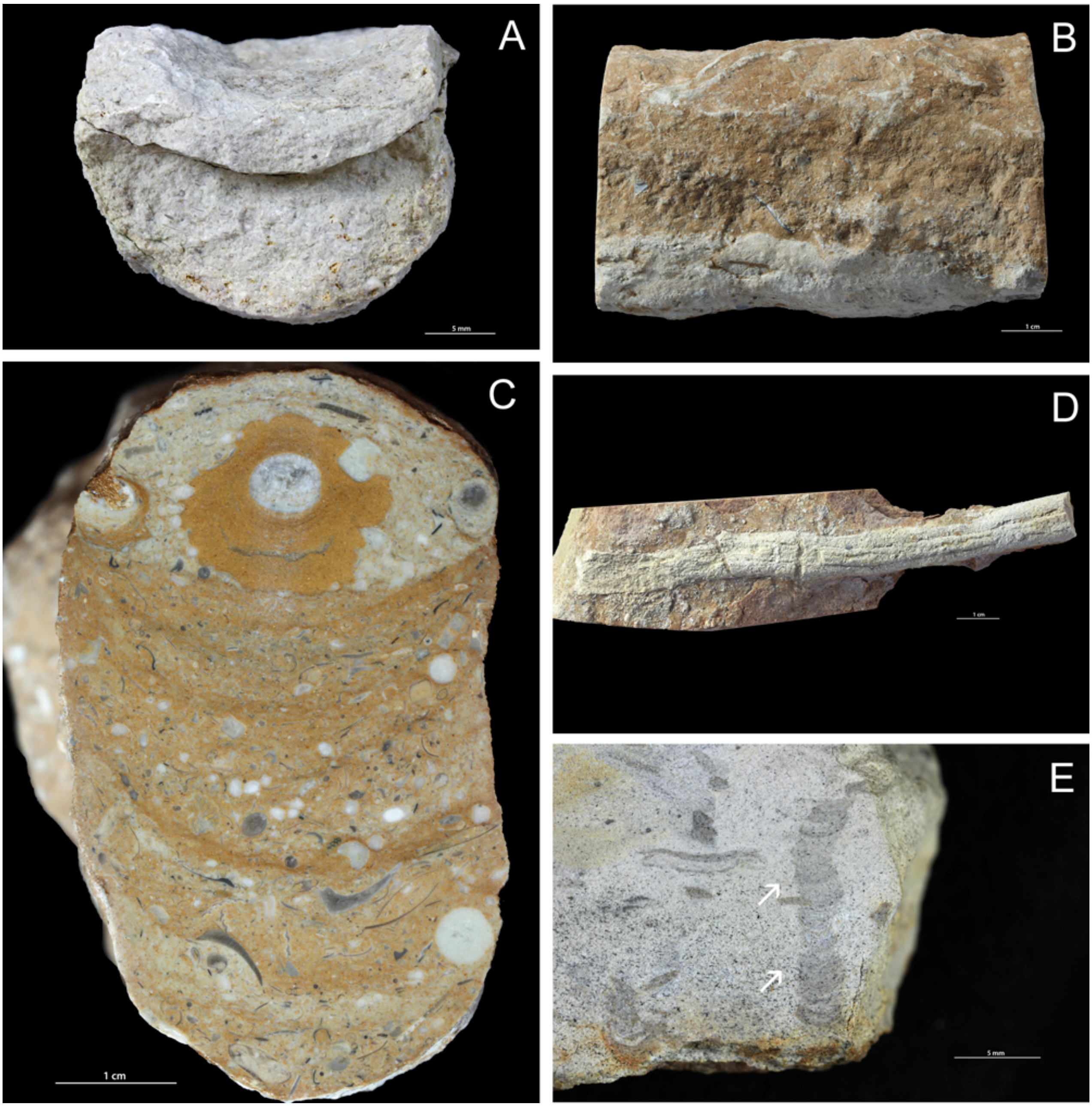

Figure 2: A, Cross section of *T. rectus* from the Haljala Regional Stage (Sandbian), northern Estonia (GIT 720-796). B, Lateral view of *T. rectus* from the Kukruse Regional Stage (Sandbian), northeastern Estonia (GIT 398-203). C, Cross section of *T. rectus* from the Kukruse Regional Stage (Sandbian), northeastern Estonia (GIT 398-203). D, Horizontal view of *T. rectus* from the Kukruse Regional Stage (Sandbian), northeastern Estonia (GIT 343-201). E, Cross section of *T. rectus* from the Adavere Regional Stage (Telychian), western Estonia (GIT 340-303). Arrows point to *Teichichnus* burrow.

5. Discussion

All *Teichichnus* burrows occur in the carbonate part of the section (Middle Ordovician to Silurian). The rarity of *Teichichnus* is not surprising in the Ordovician and Silurian of Estonia. It is a common ichnofossil in the Phanerozoic sediments and it occurs mainly in low-energy depositional systems. *Teichichnus* is usually recorded in fully oxygenated substrates (LIMA & NETTO, 2012), but it also occurs in substrates with stressful conditions and in this case specimens are generally smaller and with diminutive spreiten (BUATOIS *et al.*, 2005). Ordovician *Teichichnus* material from Estonian collections shows diminutive spreiten but it is always associated with relatively diverse ichnofauna (*Conichnus*, *Amphorichnus*, *Planolites*, *Thalassinoides*, *Taenidium*, *Phycodes)* and abundant shelly fauna. VOSSLER and PEMBERTON (1989)

Figure 3: Horizontal view of *T. patens* from the Kukruse Regional Stage (Sandbian), northeastern Estonia (GIT 360-111).

noted that *Teichichnus* behavior type is not beneficial in areas of slow and steady sedimentation rate; Estonian material originated from such areas of shallow epeiric sea and is in agreement with this idea. Findings of *Teichichnus* burrows are related with deeper environments than shoreface and also with periods of higher sedimentation rate in the Ordovician and Silurian. *Teichichnus* burrows have mostly been reported from siliciclastic rocks (SEILACHER, 1955; BUCKMAN, 1996; SEILACHER, 2007; SCHLIRF & BROMLEY, 2007; KNAUST, 2018). Fewer findings are reported form carbonates, mostly from Mesozoic chalk (*e.g.*, FREY, 1970; FREY & BROMLEY, 1985). There are important differences between the formations of trace fossils in carbonate versus siliciclastic sediments (CURRAN, 1994; KNAUST *et al.*, 2012). In carbonate rocks it is common that colour contrast is absent, which impacts the preservation of trace fossils (CURRAN, 1994). This may explain the more frequent occurrence of *Teichichnus* in kukersite bearing beds in lower Sandbian of Estonia where clear color contrast occurs between the trace filling and rock matrix.

The majority of studied *Teichichnus* specimens from Estonia have been collected from lower Upper Ordovician (Sandbian) rocks. It is likely that the more common *Teichichnus* in the lower Upper Ordovician is reflecting favorable sedimentation conditions rather than the increase in number of trace makers.

In the Cambrian, *Teichichnus* along with other Cambrian feeding burrows, is only known from shallow tier levels (BUCKMAN, 1996). Already by the Upper Cambrian-Lower Ordovician *Teichichnus* occurred at depths of up to 150 mm within deep-sea flysch sediments (PICKERILL & WILLIAMS, 1989). An Upper Cretaceous *Teichichnus* reached a depth of emplacement in excess of 1 meter (FREY & BROMLEY, 1985). *Teichichnus* in the Ordovician of Estonia seems to be confined to the shallowest tier levels. Some *Teichichnus* traces may be quite a long and not very deep as was described by LEGG (1985) from the Middle Cambrian sediments. Similar shallow traces occur in Estonian kukersite. A very stunted vertical spreiten may be related to the flimsy soft sediment layer. Alternatively, the carbonate muds contain a high content of organic matter in comparison to sands. Estonian kukersite originated from organic material (FOSTER *et al.*, 1990) and offered an environment especially rich in deposited organics. In this kind of organic rich sediment the *Teichichnus* producer could move around less frequently for successful feeding than in organic poor sediments. Thus, amount of food in the sediment could influence the tier of *Teichichnus* traces. In the Silurian of Estonia *Teichichnus* occurs in the

Osmundsbergen bentonite, where it is considerably smaller and shows relatively deeper spreiten than the Ordovician traces. It was formed in conditions where sediment accumulated rapidly; this kind of trace is interpreted as an equilibrium feeding structure (CORNER & FJALSTAD, 1993).

Different ichnospecies of *Teichichnus* have different palaeogeographic distributions. The only ichnospecies with global distribution in the Lower Paleozoic is *T. rectus* (KNAUST, 2018). Another Lower Paleozoic ichnospecies, *T. patens*, has more restricted distribution being hitherto known only from the Upper Ordovician of Bohemia (MIKULÁŠ, 1992). New findings from the Upper Ordovician of Estonia demonstrate that this ichnospecies had a wider geographic distribution than previously known.

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